Crab Cavity R&D

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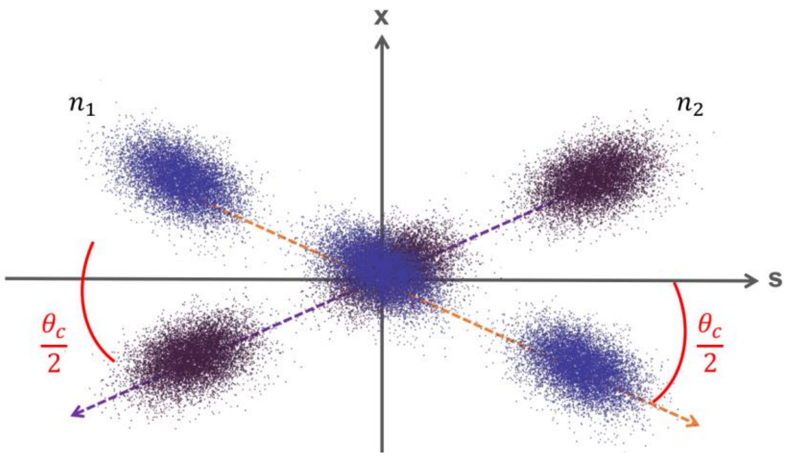
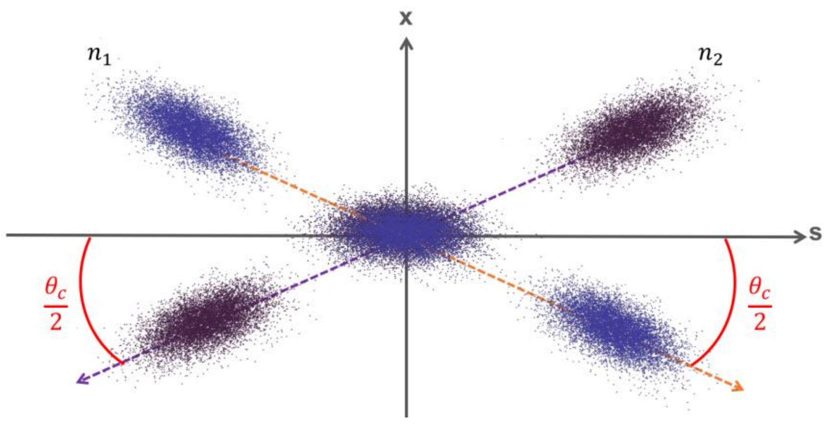
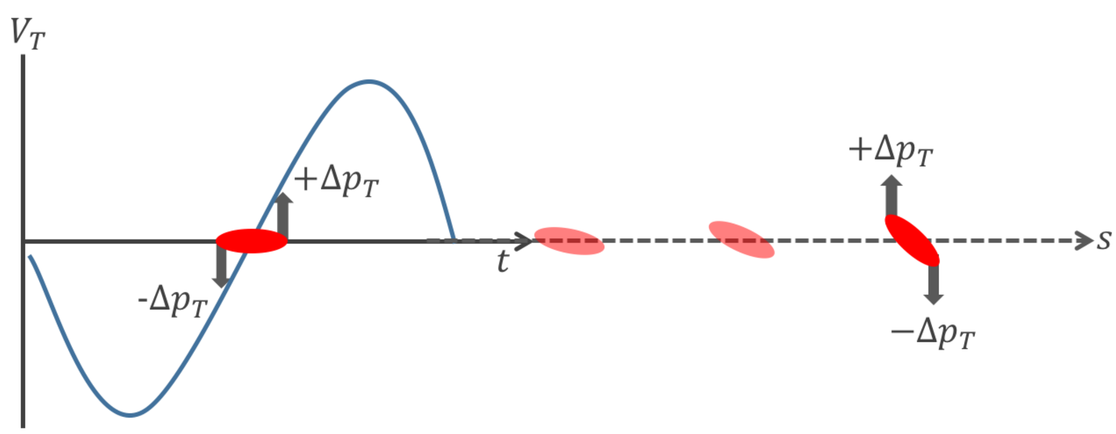
Crabbing System







$$V_T = \frac{cE_b \tan\frac{\theta_c}{2}}{2\pi f\sqrt{\beta_x^* \beta_x^C}},$$

ODU Cast of Characters on Crabbing Systems

- Subashini De Silva
  - PhD ODU 2014 : “Investigation and optimization of a new compact superconducting cavity for deflecting and crabbing applications”
  - 2015 IEEE PAST Award, 2015 ODU College of Science Lee Entsminger Outstanding PhD Dissertation Award
  - Research Scientist at ODU
  - RF separator for 12 GeV upgrade, Crabbing system for LHC High Luminosity Upgrade

- Alejandro Castilla
  - PhD ODU December 2016 : “Crabbing System for an Electron-ion Collider”
  - Now at CERN, Crabbing System for LHC High Luminosity Upgrade

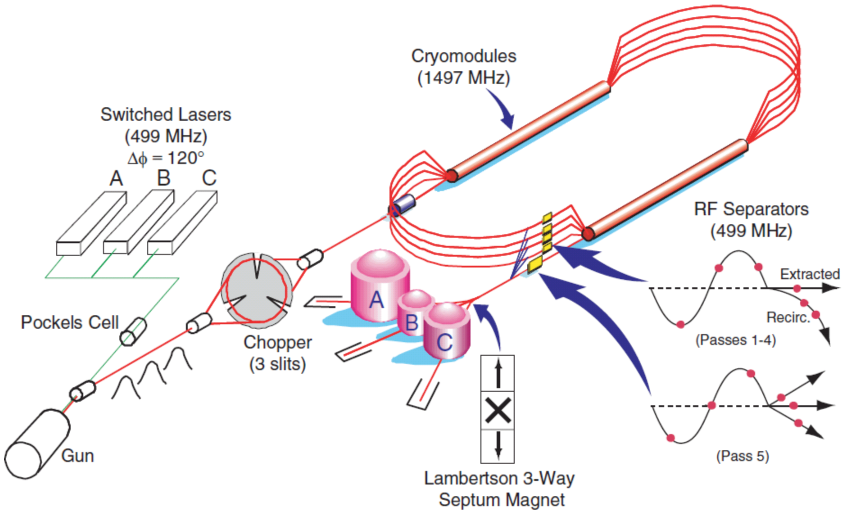
- Salvador Sosa
  - PhD student, Continuing work of Alejandro Castilla

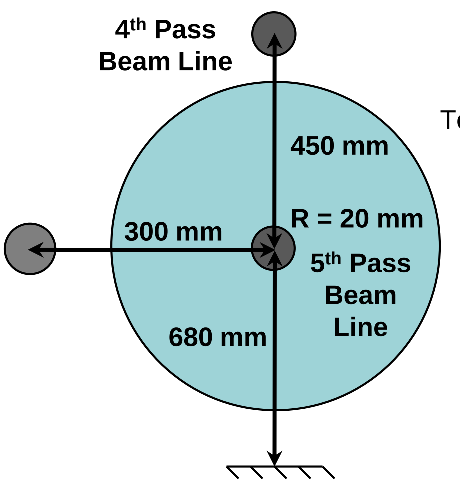
- HyeKyoung Park
  - ODU PhD Physics Student and JLab Engineer
  - Superconducting RF separator for 12 GeV upgrade
  - Crabbing system for LHC High Luminosity Upgrade

- Rocio Olave
  - ODU Post-doc, now part-time

Deflecting and Crabbing Applications

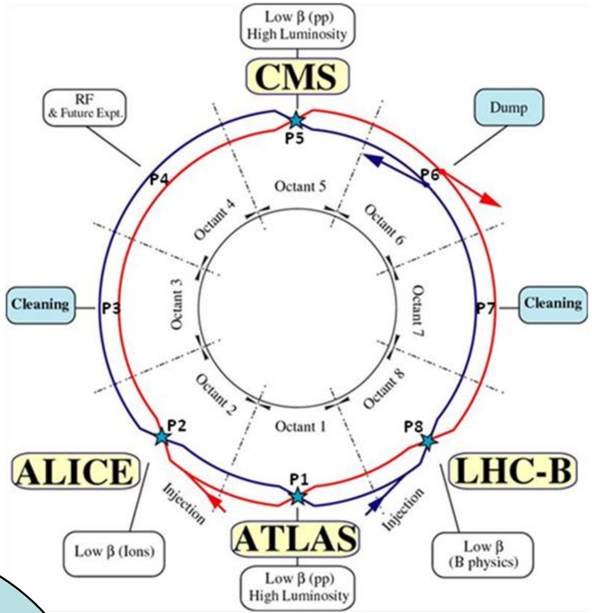
499 MHz Deflecting Cavity for Jefferson Lab 12 GeV Upgrade

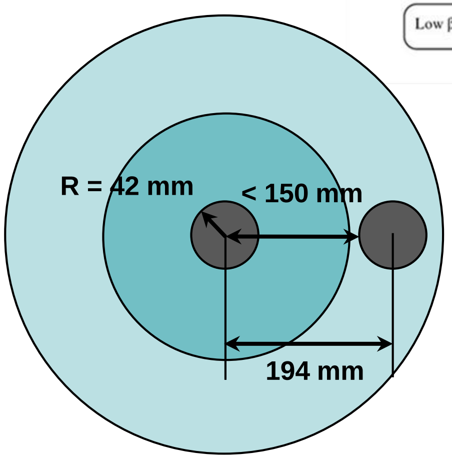




Total transverse voltage = 5.6 MV

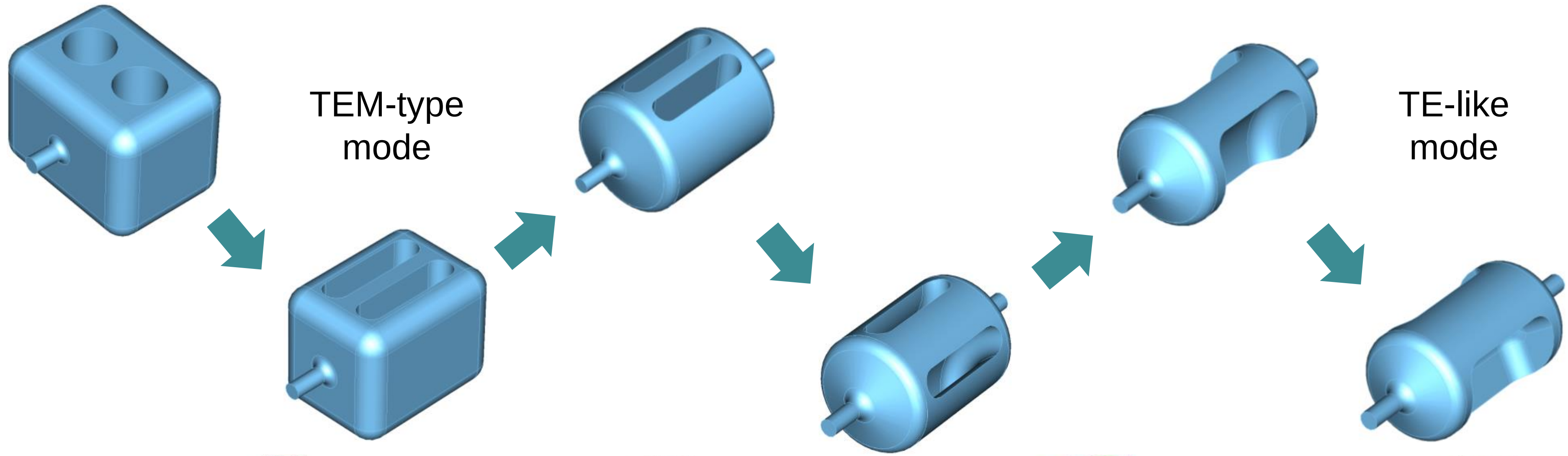
400 MHz Crabbing Cavity for LHC High Luminosity Upgrade

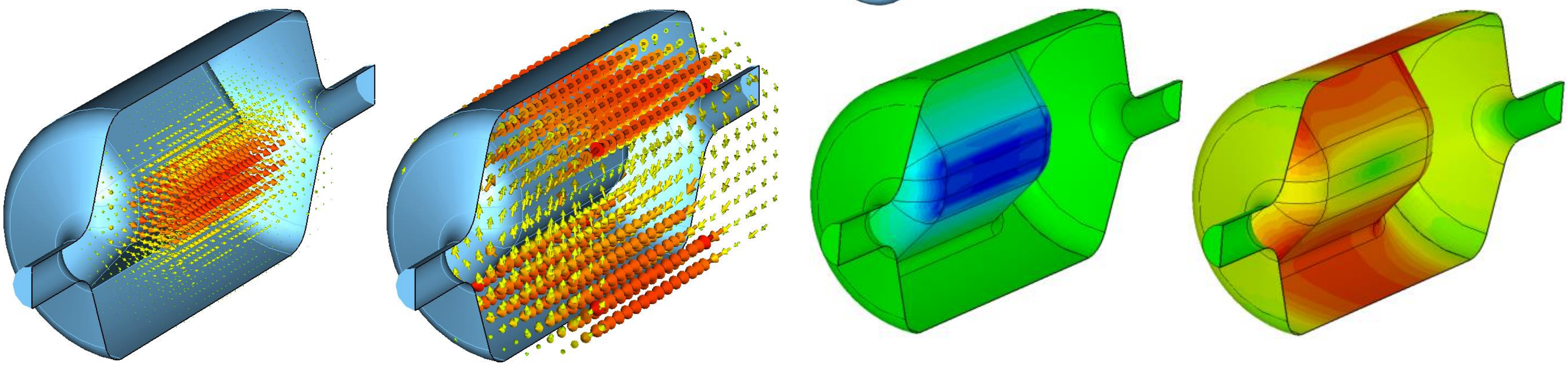




Total transverse voltage = 10 MV per beam per side

Parallel-Bar Cavity to RF-Dipole Cavity





E Field | H Field | Surface E Field | Surface H Field

S. U De Silva and J. R. Delayen, "Design evolution and properties of superconducting parallel-bar rf-dipole deflecting and crabbing cavities, PRSTAB 16, 012004 (2013)
S. U. De Silva, PhD thesis, ODU 2014

RF Dipole Cavity Properties

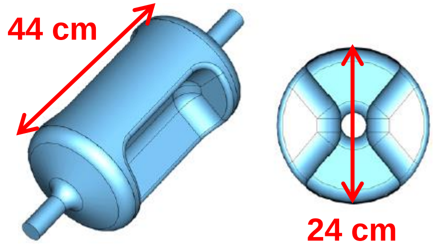
- Compact design
  - Supports low frequencies
- Fundamental deflecting/crabbing mode has the lowest frequency
  - No LOMs, no need for notch filter in HOM coupler
  - Nearest HOM widely separated (~ 1.5 fundamental)
- Low surface fields and high shunt impedance
- Good balance between peak surface electric and magnetic field
- Good uniformity of deflecting field due to high degree symmetry
- Many degrees of freedom to tailor design to application

RF-Dipole Deflecting/Crabbing Cavities

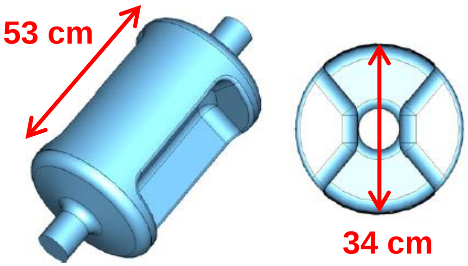
Proof-of-principle cavities

Frequency	499.0	400.0	750.0	MHz
Aperture Diameter (d)	40.0	84.0	60.0	mm
d/(λ/2)	0.133	0.224	0.3	
LOM	None	None	None	MHz
Nearest HOM	777.0	589.5	1062.5	MHz
E_p^*	2.86	3.9	4.29	MV/m
B_p^*	4.38	7.13	9.3	mT
B_p^*/E_p^*	1.53	1.83	2.16	mT/ (MV/m)
$[R/Q]_T$	982.5	287.2	125.0	Ω
Geometrical Factor (G)	105.9	138.7	136.0	Ω
$R_T R_S$	1.0×10^5	4.0×10^4	1.7×10^4	Ω^2
At $E_T^* = 1$ MV/m				

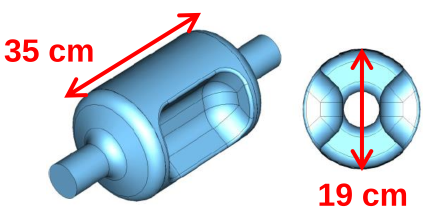
499 MHz Deflecting Cavity for Jefferson Lab 12 GeV Upgrade



400 MHz Crabbing Cavity for LHC High Luminosity Upgrade

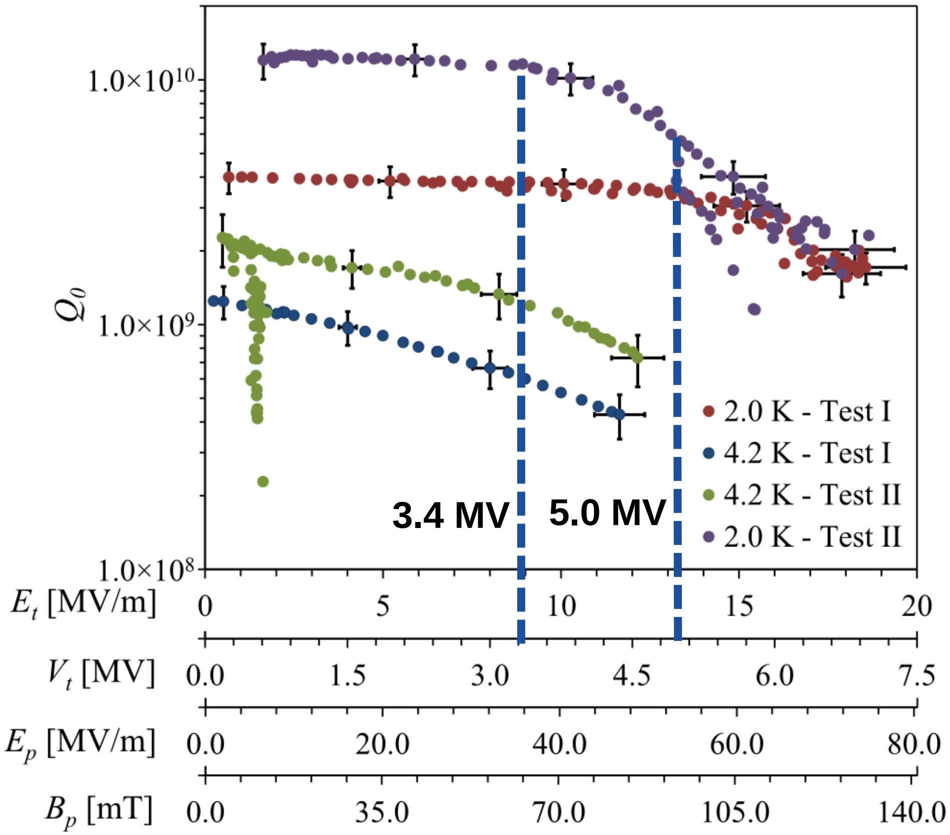


750 MHz Crabbing Cavity for MEIC at Jefferson Lab



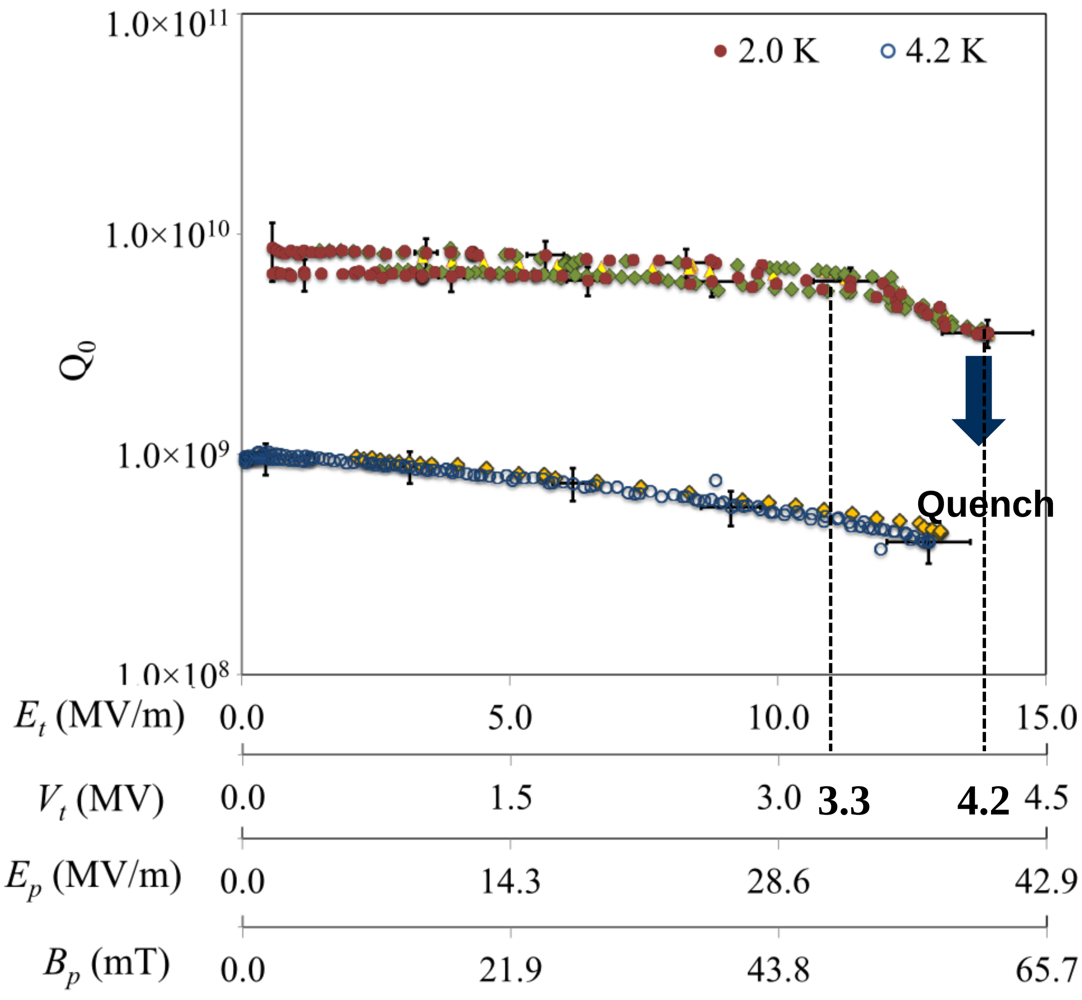
400 MHz Proof-of-Principle Cavity for LHC

- Cavity reached a V_T of 7.0 MV
  - Cavity was retested with Nb coated flanges provided by CERN
  - Q_0 increased by a factor of 3 from 4×10^9 to 1.2×10^{10}
- Multipacting was processed easily and did not reoccur
- Results were confirmed by CERN



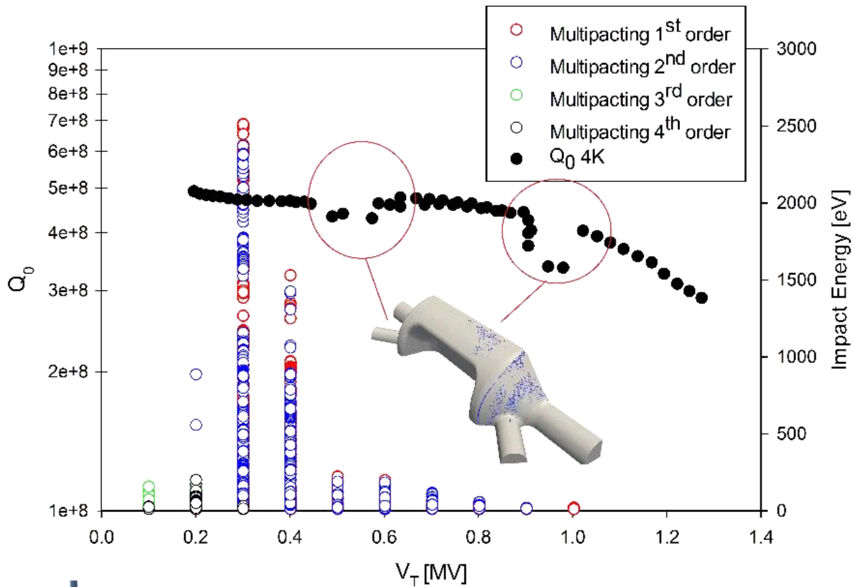
499 MHz Deflecting Cavity for JLab

Frequency	**499.0**	**MHz**
Aperture Diameter (d)	40.0	mm
Nearest HOM	777.0	MHz
E_p^*	2.86	MV/m
B_p^*	4.38	mT
B_p^*/E_p^*	1.53	mT/ (MV/m)
$[R/Q]_T$	982.5	Ω
Geometrical Factor (G)	105.9	Ω
$R_T R_S$	1.0×10^5	Ω^2
At $E_T^* = 1$ MV/m		

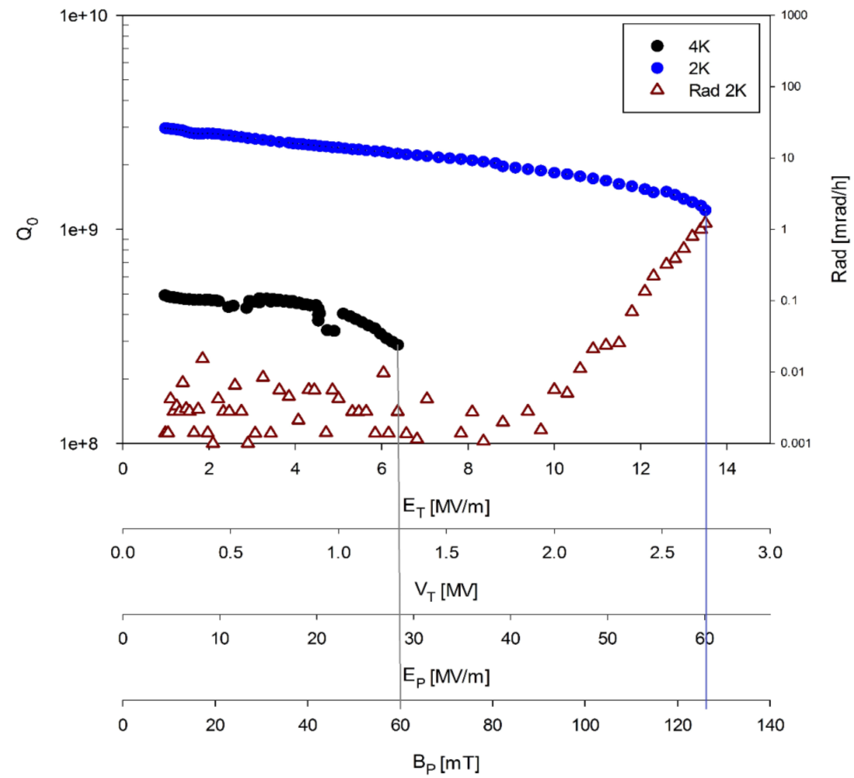


750 MHz Crabbing Cavity for Jlab MEIC

Multipacting

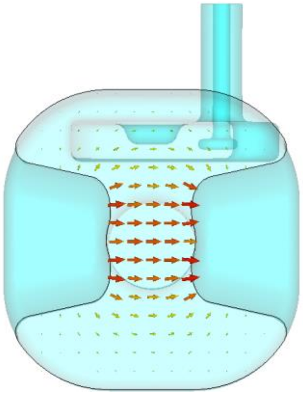


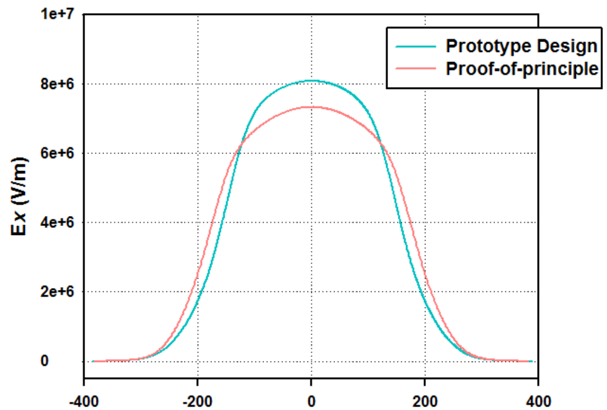
Cryogenic Tests



$$E_T = 13.5\ MV/m$$
$$V_T = 2.7\ MV$$
$$E_P = 60\ MV/m$$
$$B_P = 126\ mT$$

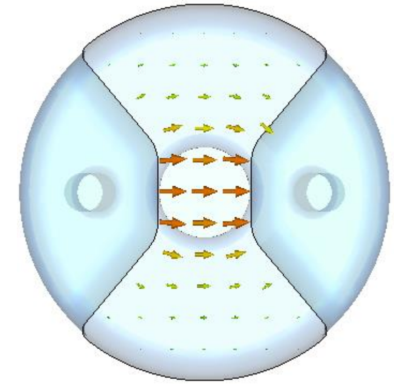
Prototype Design vs. Proof-of-Principle





* At energy content of 1 J

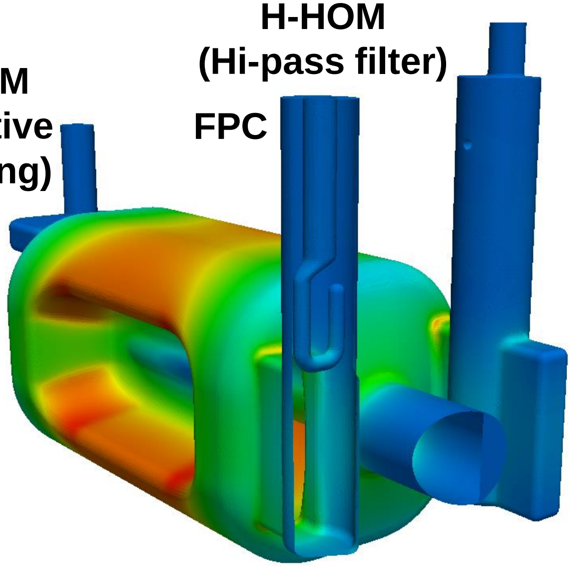
Transverse Electric Field



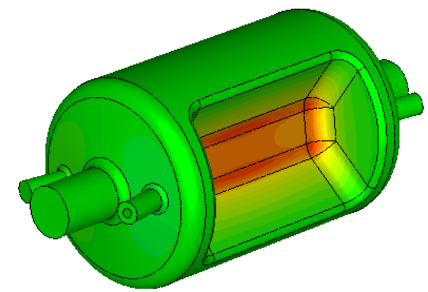
H-HOM (Hi-pass filter)

V-HOM (selective coupling)

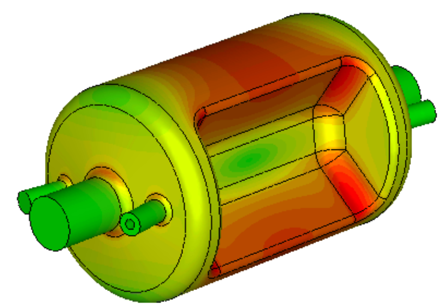
FPC



Surface Electric Field

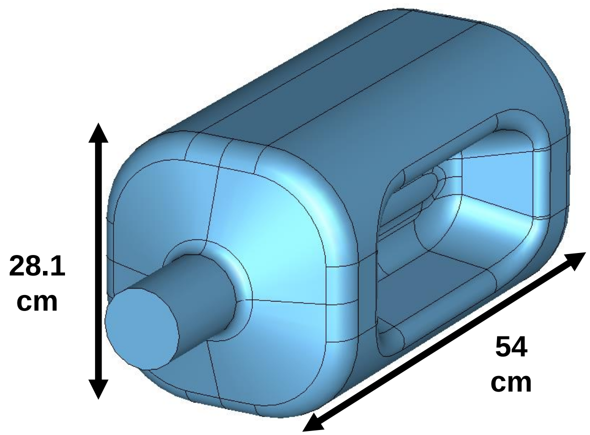


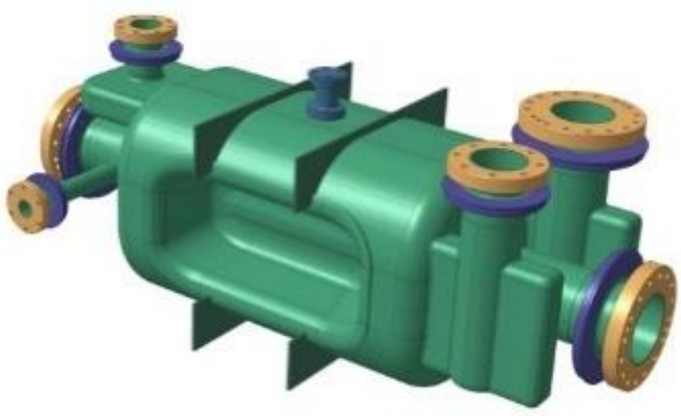
Surface Magnetic Field



Prototype RF Dipole Design

Prototype design has improved rf-properties

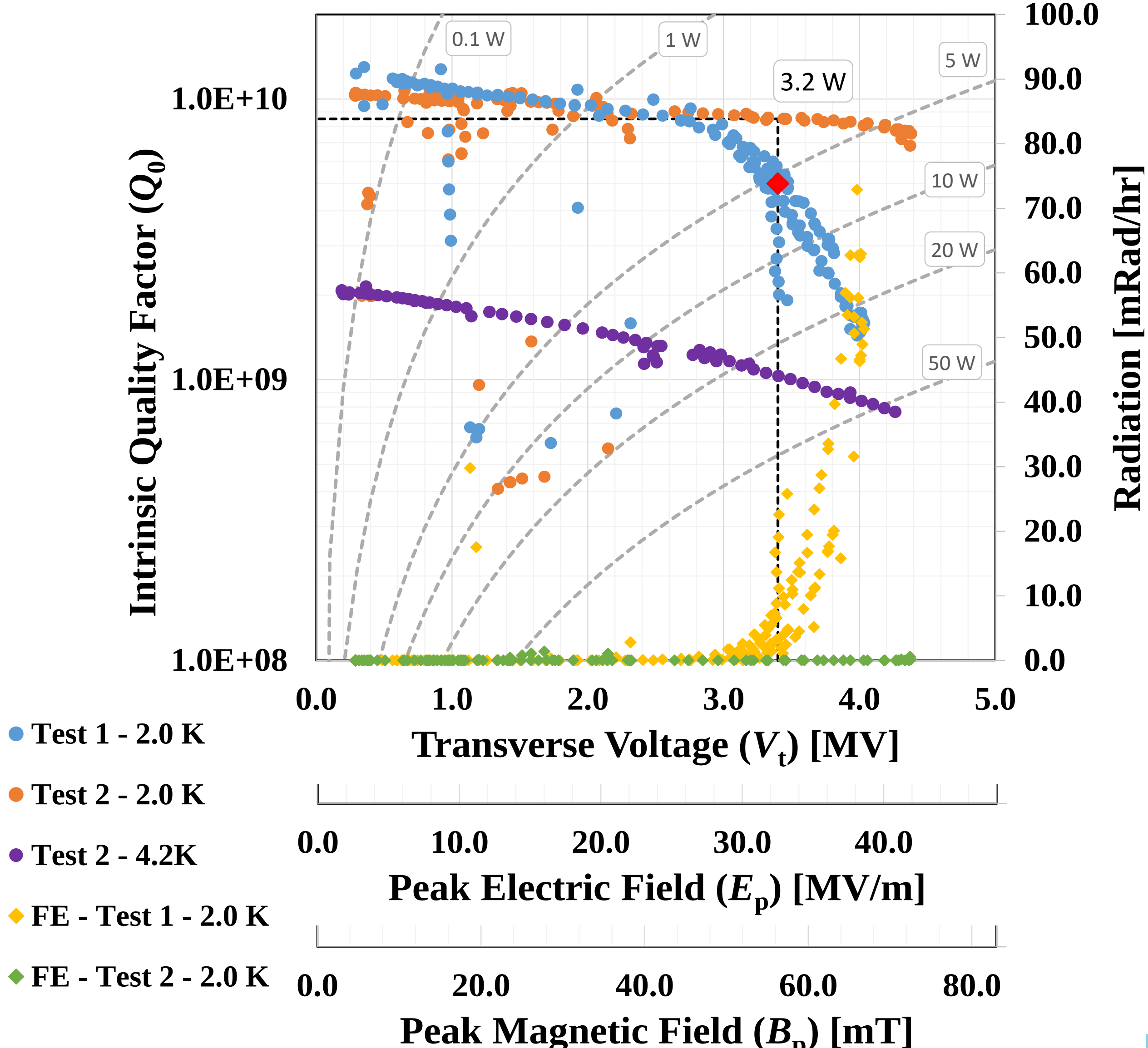




Parameters	Prototype	P-o-P	Units
Frequency of fundamental	400	400	MHz
Frequency of 1st HOM	632	590	MHz
Deflecting Voltage (V_T^*)	0.375	0.375	MV
Peak Electric Field (E_p^*)	3.65	4.02	MV/m
Peak Magnetic Field (B_p^*)	6.22	7.06	mT
Peak Electric Field (E_p^{**})	32.6	35.9	MV/m
Peak Magnetic Field (B_p^{**})	55.6	63.1	mT
B_p/E_p	1.71	1.76	mT/(MV/m)
Stored Energy (U^*)	0.13	0.195	J
$[R/Q]_T$	427.4	287.0	Ω
Geometrical Factor (G)	106.7	140.9	Ω
$R_T R_S$	4.6×10^4	4.0×10^4	Ω^2
*At E_T = 1 MV/m ** At V_T = 3.35 MV			

Cavity and HOM Couplers Fabrication

SPS-RFD Cavity Test Results

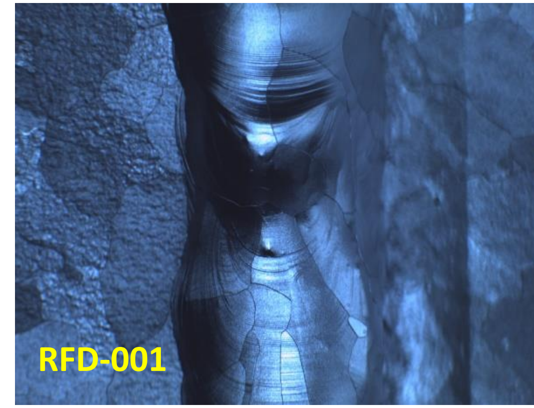


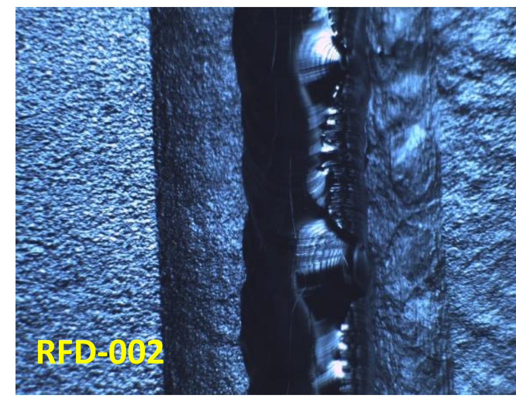
- At low fields for both rf tests Q_0 is > 1.0×10^{10}
- Multipacting was processed easily and didn't reoccur
- No field emission observed during Test 2

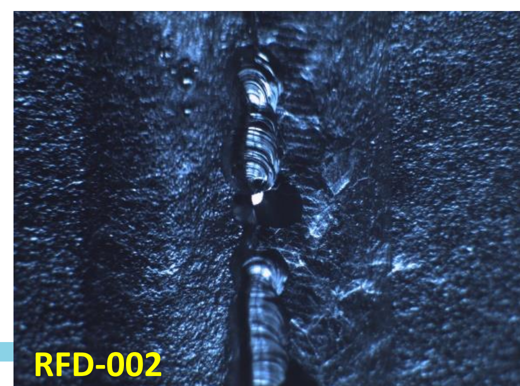
At 2.0 K	Test 1	Test 2
Max V_t [MV]	4.0 MV	4.4 MV
E_p [MV/m]	38	42
B_p [mT]	66	73
Q_0 at 3.4 MV	5.5×10^9	8.5×10^9
R_s [nΩ]	10.5	12.6

Lessons Learned

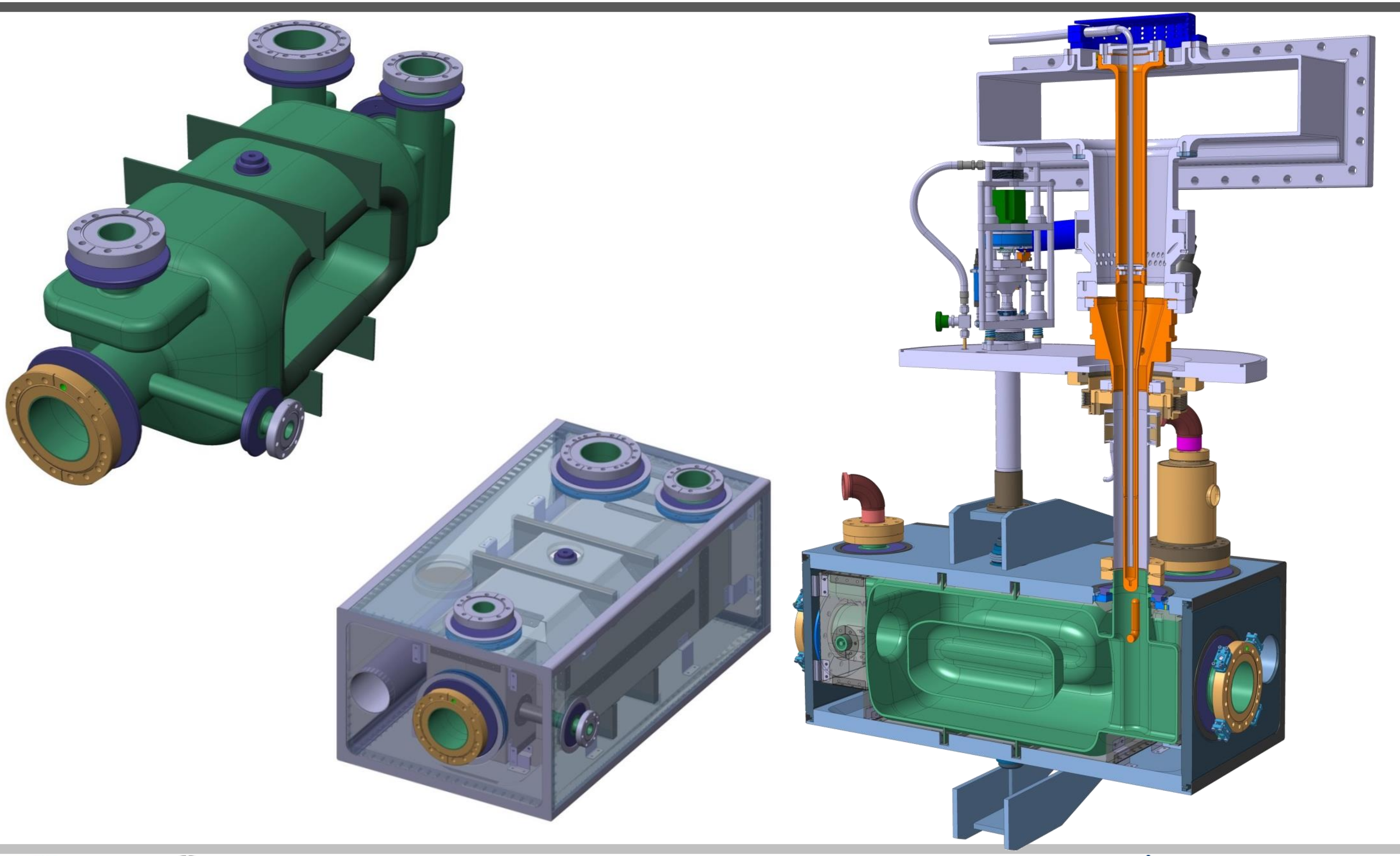
- Perform bulk BCP after final weld
- Bulk BCP of the two SPS-RFD cavities were done before final weld to control frequency shift due to processing
- Due to quality of final welds additional bulk BCP was done on both RFD cavities
- Frequency shift due to bulk BCP → 40 kHz (140 microns uniform removal)
- Frequency shift is comparatively small → Not a critical parameter in frequency control



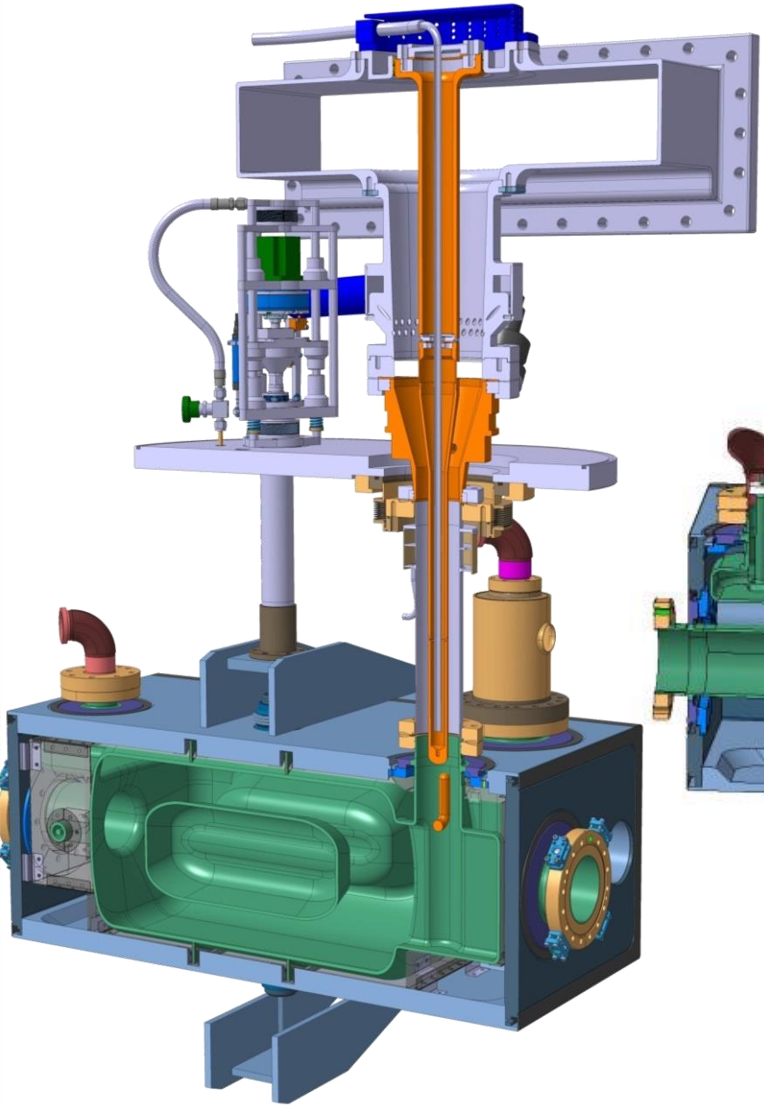


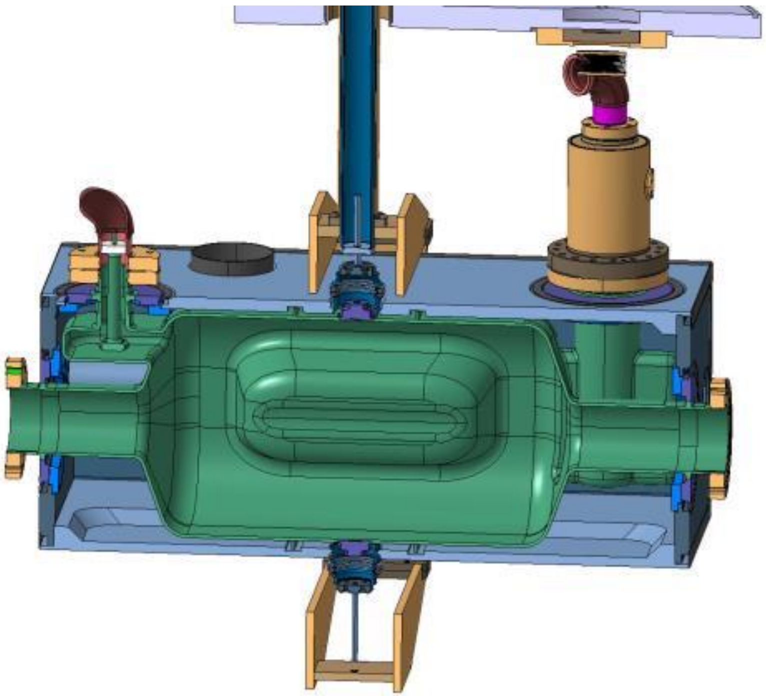


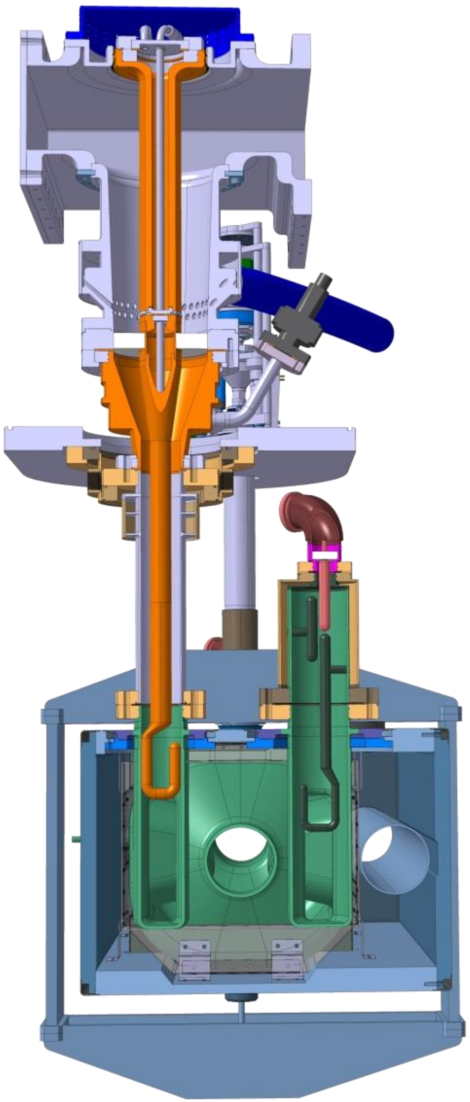
Magnetic Shielding and Helium Tank



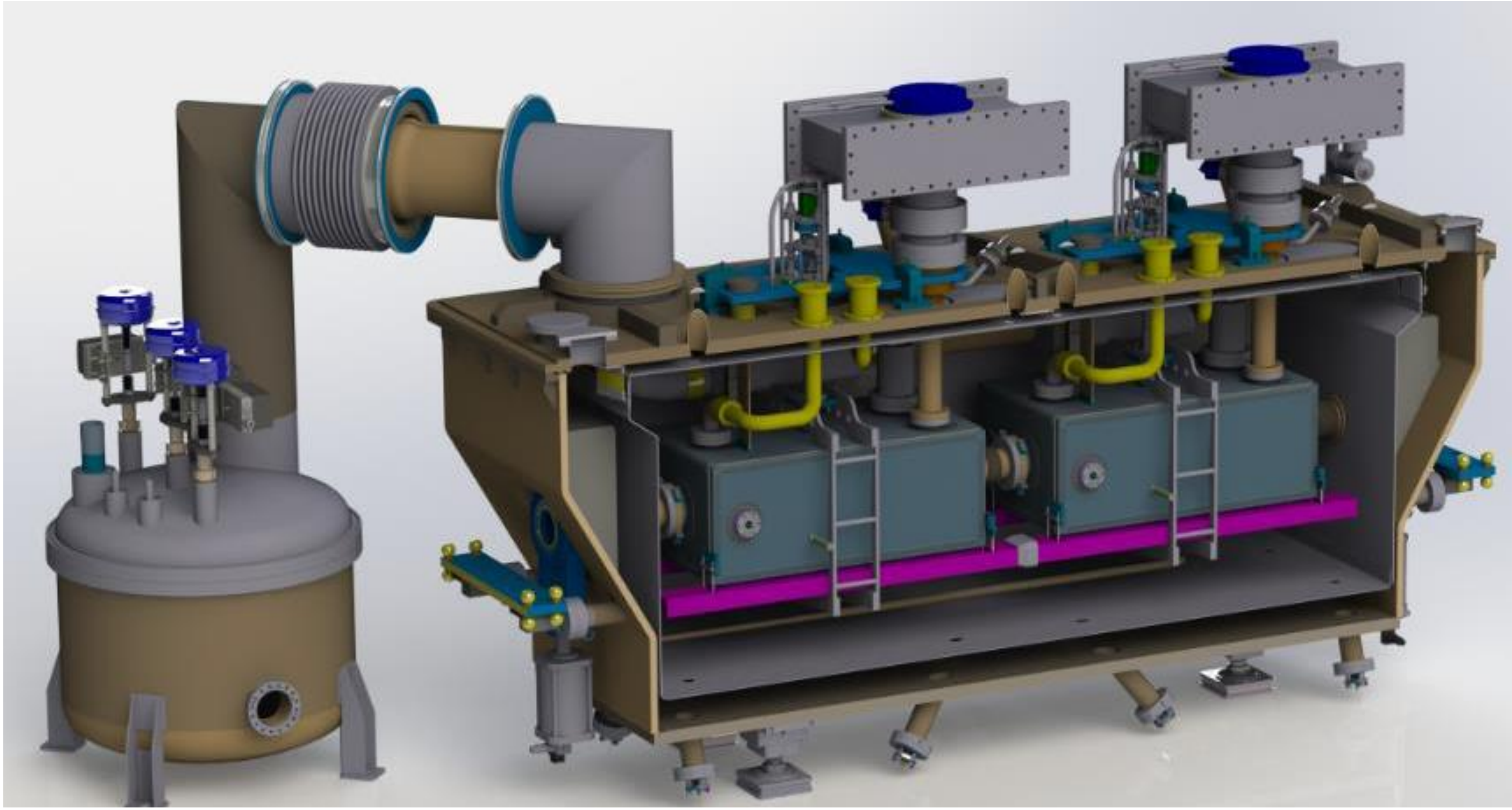
Tuner Engineering







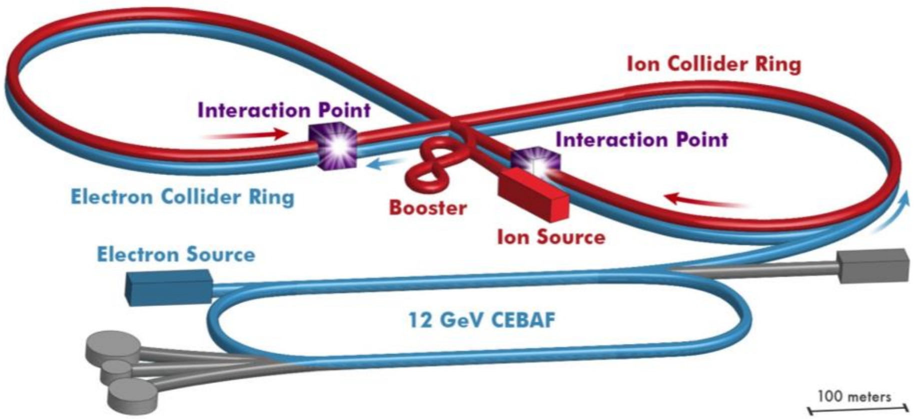
Cryostat Engineering

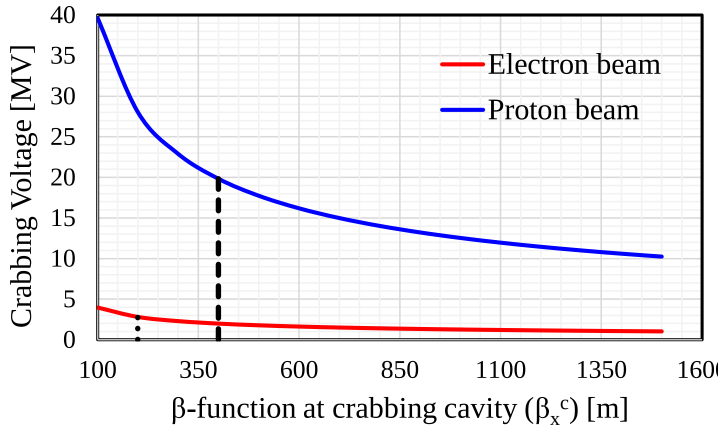


Crabbing Cavity for JLEIC

- Horizontal local crabbing system
  - Two interaction points
  - Four crabbing cavity locations – per interaction point (per beam - per side)
- Crabbing cavity frequency – 952.6 MHz
- Luminosity > 10^{33} $cm^{-2}s^{-1}$

Parameter	Electron	Proton	Units
Beam energy	10	100	GeV
Beam current	0.72	5.0	A
Bunch frequency	952.6		MHz
Crab crossing angle	50		mrad
Betatron function at IP	10		cm
Betatron function at crab cavity	200	363	m
Integrated transverse voltage per beam per side	2.8	20.8	MV



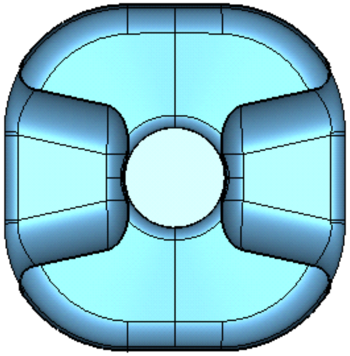


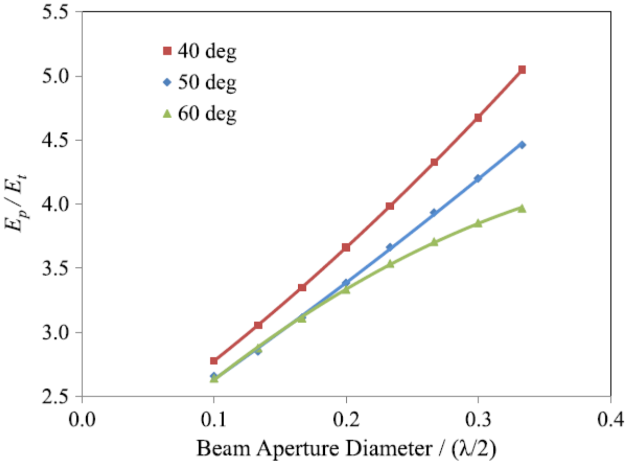
Challenges for JLEIC Crabbing System

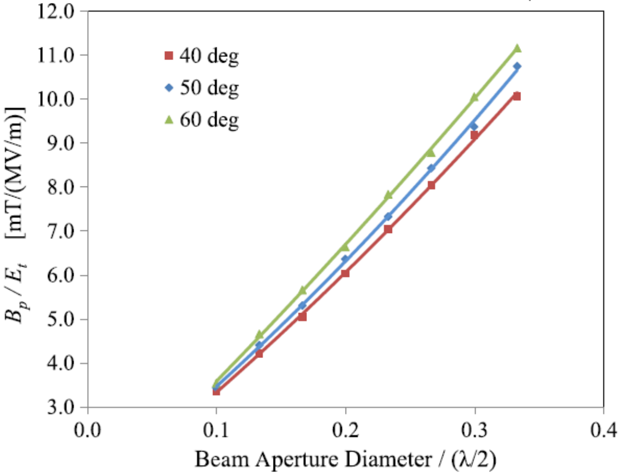
- Higher frequency than demonstrated so far
  - Properties degrade rapidly as ratio of aperture to wavelength increases
- Constraints on transverse and longitudinal space available
  - Multi-cell cavities
- Crabbing in continuously variable direction
  - Independent and simultaneous horizontal and vertical crabbing
  - Not anymore in baseline

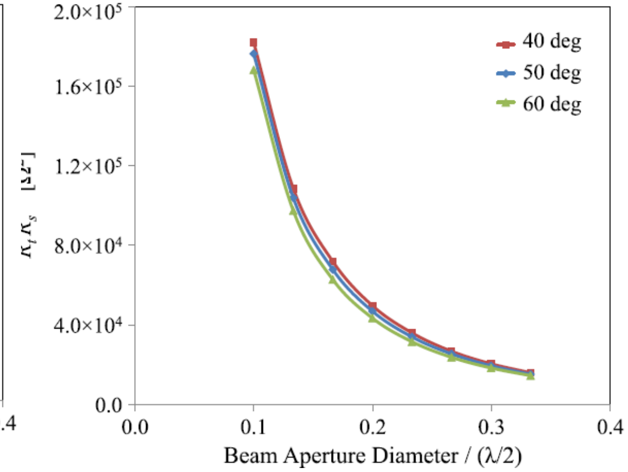
Aperture-dependent Properties

- Electromagnetic properties of “TE” cavities are quite sensitive to beamline aperture (separation between the poles)



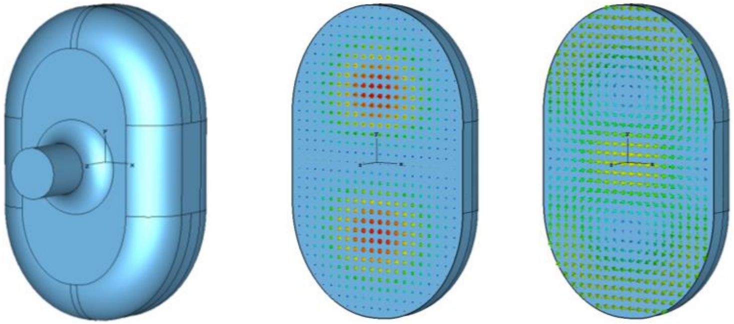




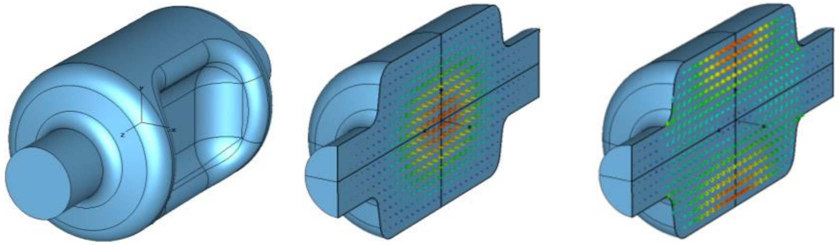


Cavity Options for Crabbing System

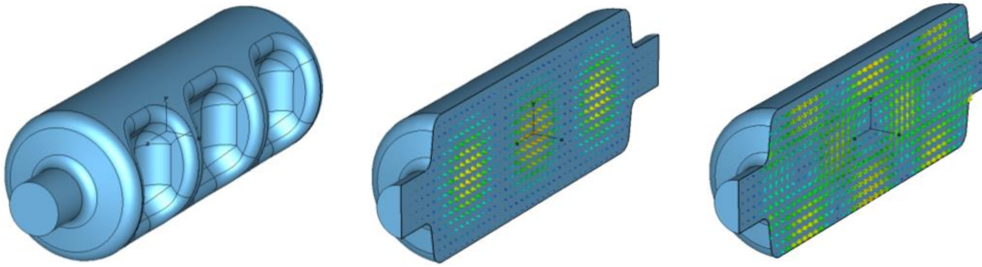
- Squashed elliptical cavity



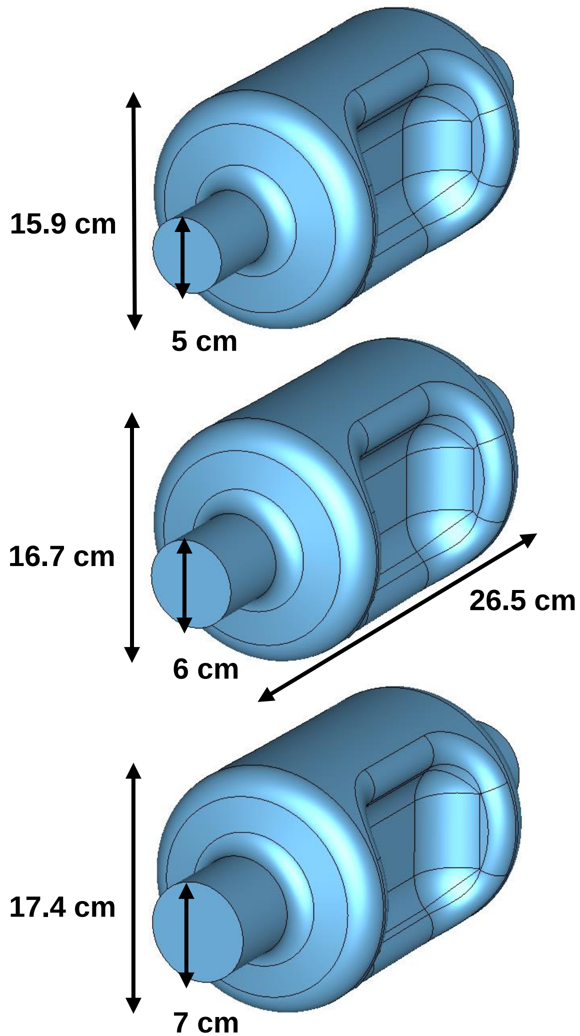
- Single-cell RF-Dipole cavity



- Multi-cell RF-Dipole cavity



952.6 MHz Cavity – Single Cell Cavity

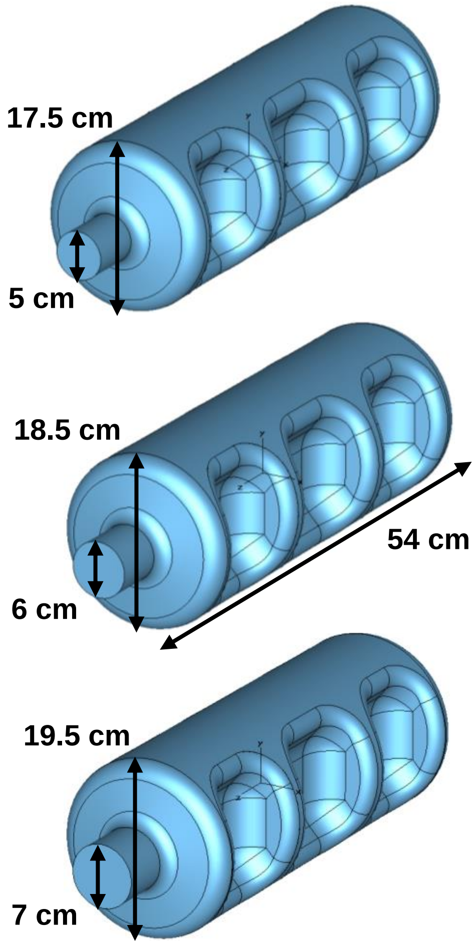


- Compact design
- No lower order modes
- Properties degrade drastically with increasing beam aperture

	(A)	**(B)**	**(C)**	
Frequency		**952.6**		**MHz**
Aperture	50	60	70	mm
1st HOM	1431.0	1420.4	1411.5	MHz
V_t^*		0.157		MV
E_p^*	4.2	4.8	5.4	MV/m
B_p^*	9.3	11.3	13.6	mT
$[R/Q]_t$	136	81	50	Ω
G	145	155	166	Ω
R_tR_s	2.0×10^4	1.3×10^4	8.3×10^3	Ω^2
$^*E_t$ = 1 MV/m				

952.6 MHz Cavity – Multi-Cell Cavity

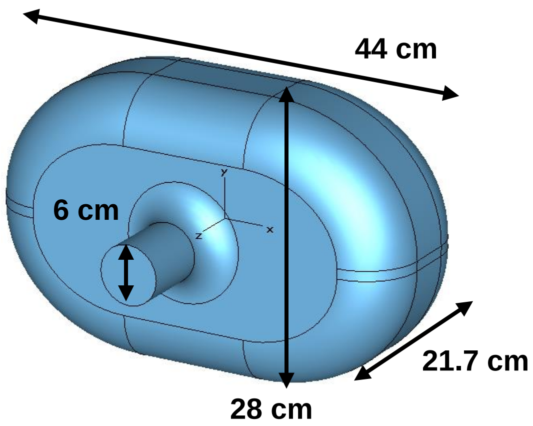
- A 3-cell design study with varying beam aperture

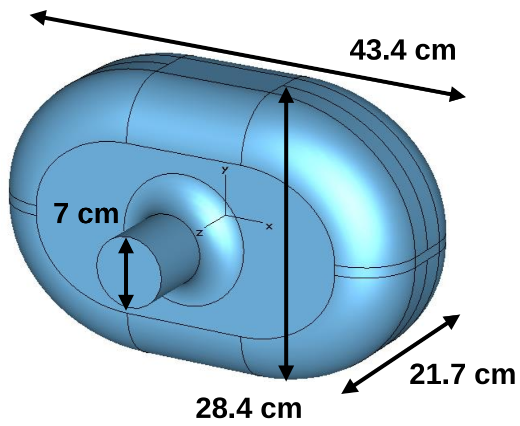


- Two lower order modes – 1st and 2nd harmonic of the crabbing mode
- High shunt impedance
- Similar peak surface fields as single cell cavity

	(A)	(B)	(C)	
Frequency	**952.6**			**MHz**
Aperture	50	60	70	mm
LOM	790, 879	773, 870	757, 862	
1st HOM	1409	1383	1335	MHz
V_t^*	0.157			MV
E_p^*	4.7	5.1	5.6	MV/m
B_p^*	8.7	10.0	11.4	mT
$[R/Q]_t$	494	323	219	Ω
G	161	170	179	Ω
R_tR_s	8.0×10^4	5.5×10^4	3.9×10^4	Ω^2
$^*\ E_t = 1$ MV/m				

952.6 MHz Squashed Elliptical Cavity





- Squashed elliptical design has reduced peak surface fields
- Has a monopole – lower order mode
- Requires wide beam pipe separation

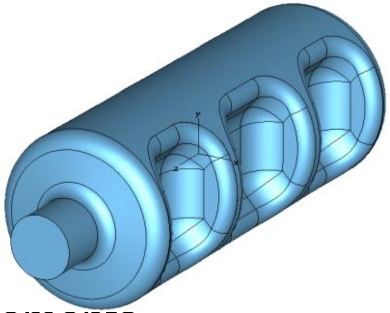
	(A)	(B)	
Frequency	**952.6**		**MHz**
Aperture	60	70	mm
LOM	699.4	697.6	MHz
1st HOM	1041.1	1033.1	
V_t^*	0.157		MV
E_p^*	2.16	2.29	MV/m
B_p^*	7.2	7.46	mT
$[R/Q]_t$	50.8	49.4	Ω
G	342.9	340.8	Ω
R_tR_s	2.75×10^4	1.7×10^4	Ω^2
$^* E_t = 1$ MV/m			

Design Comparison

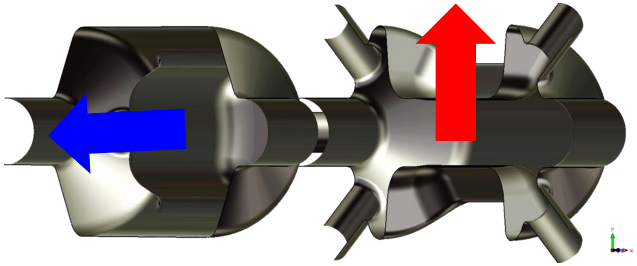
	Squashed Elliptical	**Single-Cell RFD**	**Multi-Cell RFD**	**Unit**
Frequency	**952.6**			**MHz**
Aperture	**70**			mm
LOM	697.6	None	757, 862	MHz
LOM Mode Type	Monopole		Dipole	
1st HOM	1033.1	1411.5	1335	MHz
Total V_t (e/p) (per beam per side)	2.8 / 20.8			MV
V_t (per cavity)	2.2	1.2	4.2	MV
No. of cavities (per beam per side)	**2 / 10**	**3 / 18**	**1 / 5**	
E_p	32	41.2	49.8	MV/m
B_p	104.3	103.7	101.4	mT
R_s [R_{res} =10 nΩ & 2.0 K]	16.3			nΩ
P_{diss} (per cavity)	4.6	2.8	7.4	W

R&D Plan for Crabbing System for JLEIC

- Year 1: Integration of beam physics requirements and crabbing system design
  - Define the beam physics requirements and constraints on crabbing system
    - Voltage
    - Impedance
    - Multipoles
    - HOM damping requirements
    - Smallest beam aperture compatible with beam physics requirements
    - Multi-cell geometries, other geometries



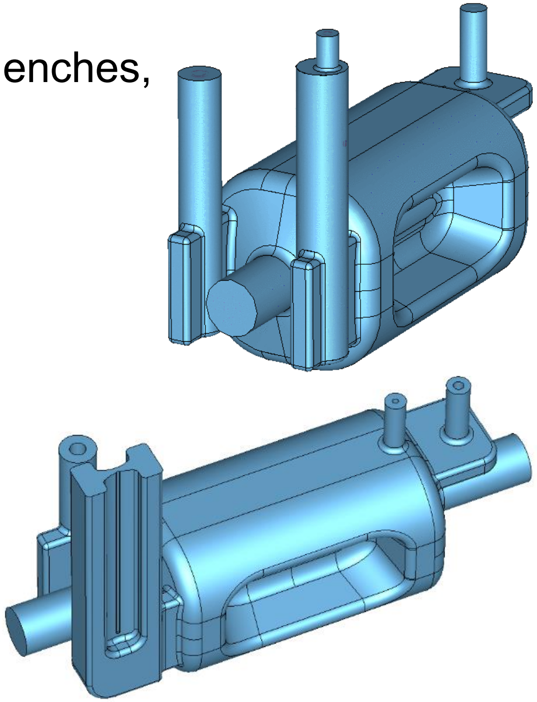
  - ~~Crabbing at "arbitrary angle"~~
    - Include horizontal and vertical crabbing cavities



  - Will required close interaction and iteration between beam physics and cavity design

R&D Plan for Crabbing System for JLEIC

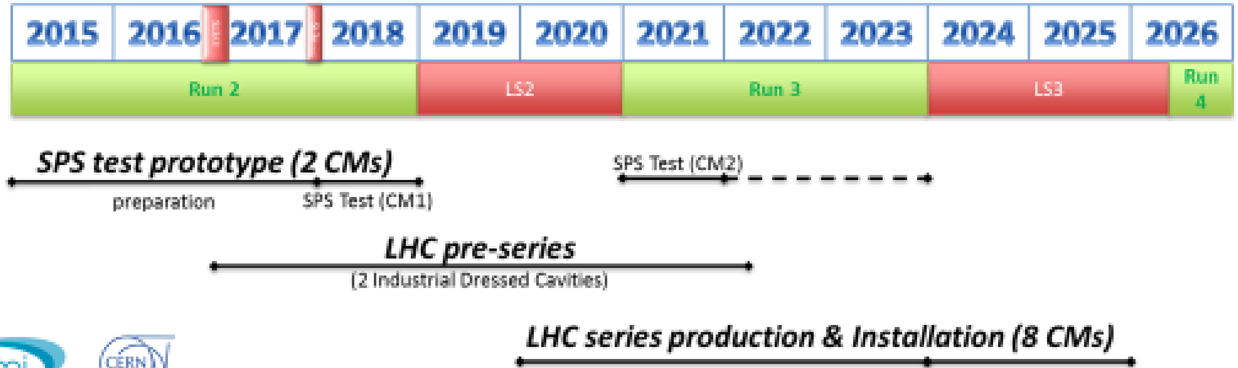
- Years 2 and 3: Design and prototyping
  - Cavity prototype design (driven by beam physics)
    - Aperture
    - Impedances (HOM damping requirement)
    - Nonlinearities and instabilities (Multipole components, quenches,
    - Multipacting simulations
  - HOM couplers design and prototyping
  - Cavity prototype fabrication and testing
  - HOM couplers fabrication and testing



Test of Crab Cavities with Hadron Beam

General plans

- 2 cryomodules for SPS tests
  - 1 cryomodule with 2 identical cavities (type «vertical» - DQW)
    - Design as much as possible coherent with LHC
    - To be tested in SPS in 2018
  - 1 cryomodule with 2 identical cavities (type «horizontal» - RFD)
    - Design to be done as LHC prototype
    - To be tested in SPS after LS2, in 2021
- 2 cavities pre-series for LHC (one of each type)
- 8 cryomodules (4 of each type) for installation in LHC during LS3
  + 2 spares (1 of each type)



OC, International Review of the Crab Cavities Performance, 3 April 2017

Work Plan for Proof-of-Principle

- Quarter 1: Beam physics study
  - Initiate electromagnetic design study
  - Initiate beam physics requirements and specifications
    - Transverse voltage for both electron and proton beams
    - Requirements on HOM impedance
    - Requirements on multipole components

- Quarter 2: Electromagnetic design with beam physics
  - Determine smallest beam aperture compatible with beam physics
  - Investigate preliminary rf designs of cavities: rf-dipole (single and multi-cell, squashed TM_{110})

Work Plan for Proof-of-Principle

- Quarter 3: Electromagnetic design with beam physics
  - Requirements completed
    - Transverse voltage for both electron and proton beams
    - Requirements on HOM impedance
    - Requirements on multipole components
  - Electromagnetic design
    - Down select between rf-dipole and TM_{110} geometries
    - Optimize rf geometry for best rf properties
    - HOM study
    - Multipacting analysis
  - Initiate engineering design
  - Initiate HOM and FPC coupler design
  - Procurement of material
    - Agreement with ODURF that PoP cavity can be capitalized (no overhead on material)

Work Plan for Proof-of-Principle

- Quarter 4:
  - Electromagnetic design and beam physics
    - Higher order modes
    - Impedances
  - Engineering design
    - Complete engineering design
    - Initiate fabrication
    - Design tooling fixtures
    - Design tooling
  - Procurement of material

Work Plan for Proof-of-Principle

- Quarter 5:
  - Electromagnetic design and beam physics
    - Higher order modes
    - Impedances
    - Multipoles
    - Complete design of HOM couplers
  - Fabrication
    - Dies and tooling fixtures
    - Initiate fabrication of Cu or Al cavity
    - Initiate fabrication of Nb cavity

- Quarter 6:
  - Electromagnetic design and beam physics
    - Higher order modes
    - Impedances
    - Multipoles
  - Complete fabrication of cavity parts

Work Plan for Proof-of-Principle

- Quarter 7:
  - Electromagnetic design and beam physics
    - Higher order modes
    - Impedances
    - Multipoles
    - Instabilities
  - Complete cavity fabrication
  - Room temperature measurements and testing
    - Higher order modes frequencies and impedances
    - Multipoles
- Quarter 8:
  - Room temperature measurement and testing
    - Higher order modes frequencies and impedances
    - Multipoles
  - Nb Cavity processing
  - Cryogenic testing of Nb cavity

Additional Slides

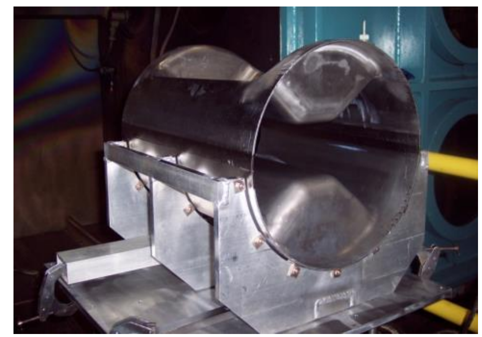
Fabrication

499 MHz Deflecting Cavity

Fabricated at Jefferson Lab

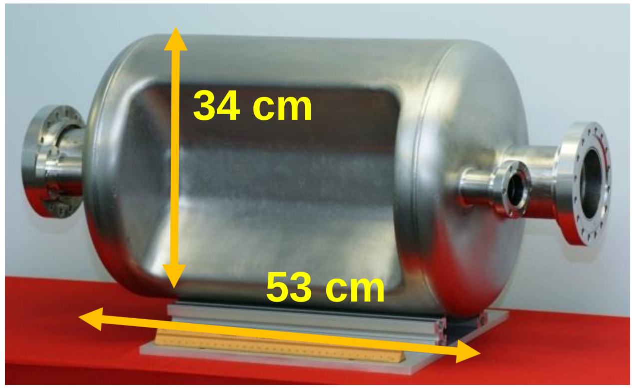
400 MHz Crabbing Cavity

Fabricated at Niowave Inc.

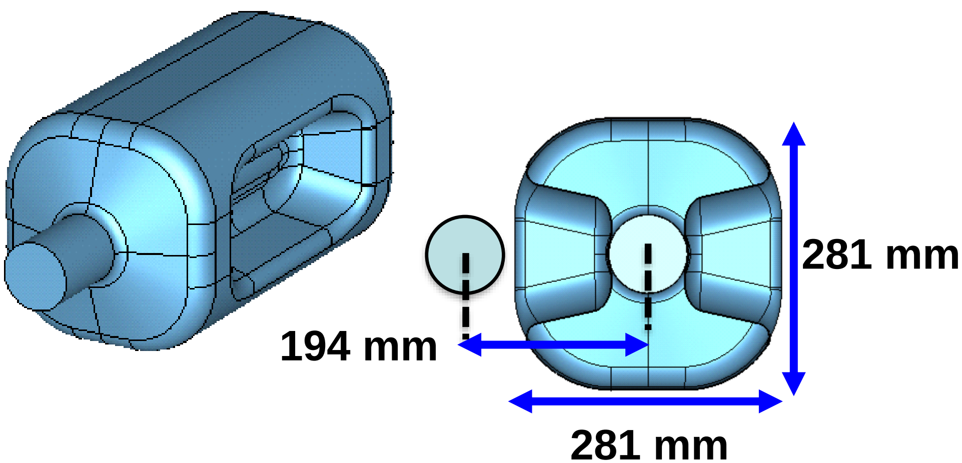


RF-Dipole Crabbing Cavity

Proof of Principle Cavity



Prototype Cavity



	P-o-P Cavity	Prototype Cavity	
Frequency	**400**	**400**	**MHz**
1st HOM	590	633.5	MHz
V_t	3.4		MV
E_p	37	33	MV/m
B_p	64	57	mT
$[R/Q]_t$	287	430	Ω
G	141	107	Ω
R_tR_s	4.0×10^4	4.6×10^4	Ω^2

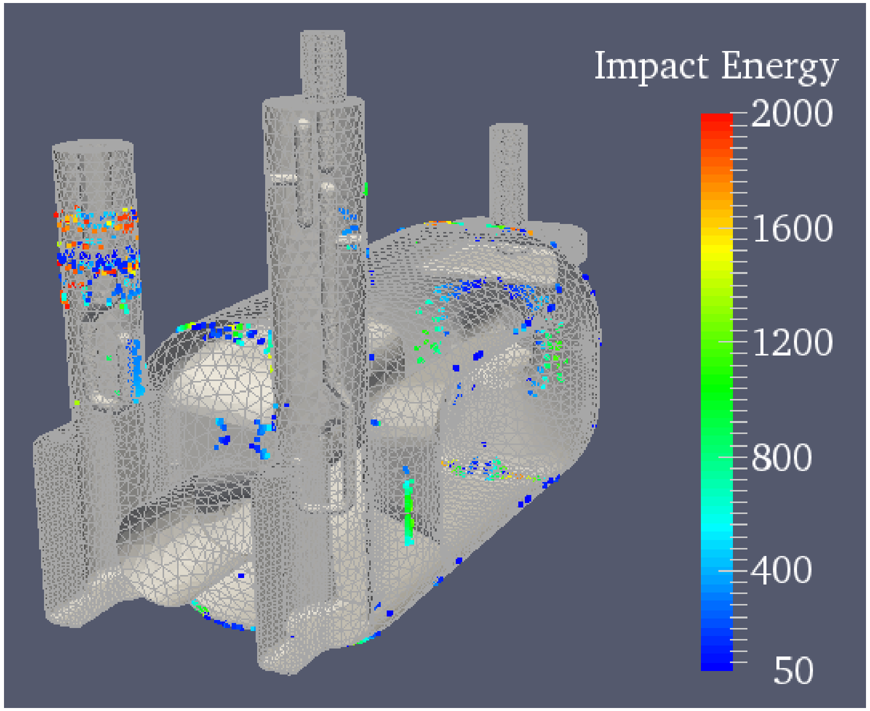
Prototype cavity

- Well separated HOMs
- Reduced surface electric and magnetic fields
- High shunt impedance
- Improved multipacting levels compared to P-o-P cavity
- Reduced multipole components

*S.U. De Silva and J.R. Delayen, PRAB 16, 012004 (2013)
#S.U. De Siva and J.R. Delayen, PRAB 16, 082001 (2013)

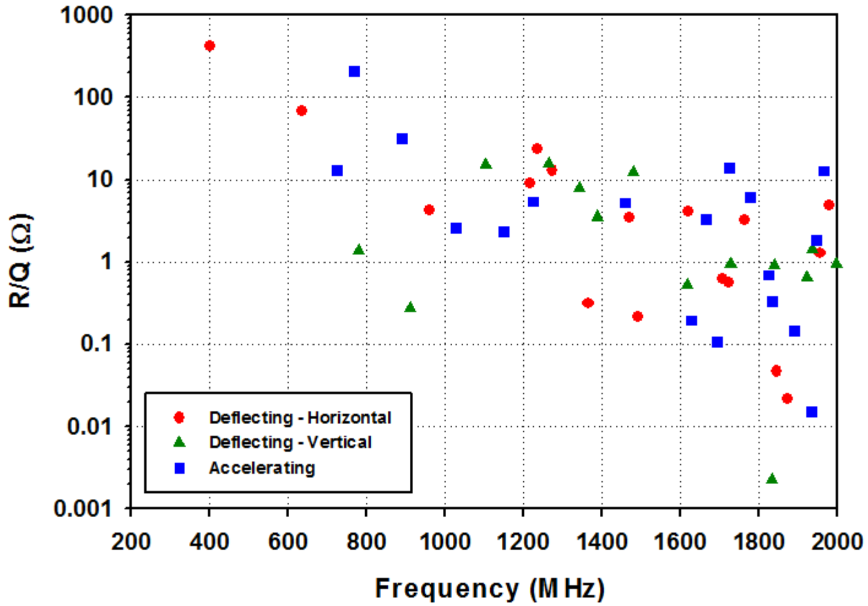
Multipacting

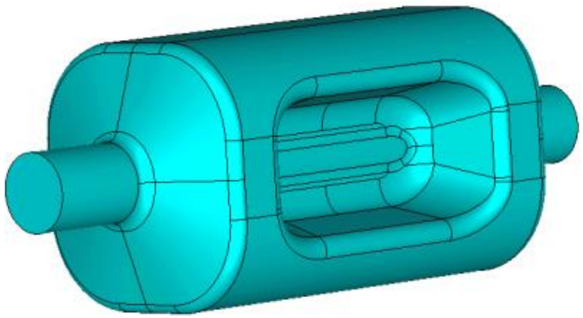
- Extensive simulations of multipacting have been performed using the SLAC ACE3P suite of codes
- Multipacting occurred in the proof-of-principle cavities where predicted, was easily processed, and did not reoccur



HOM Damping

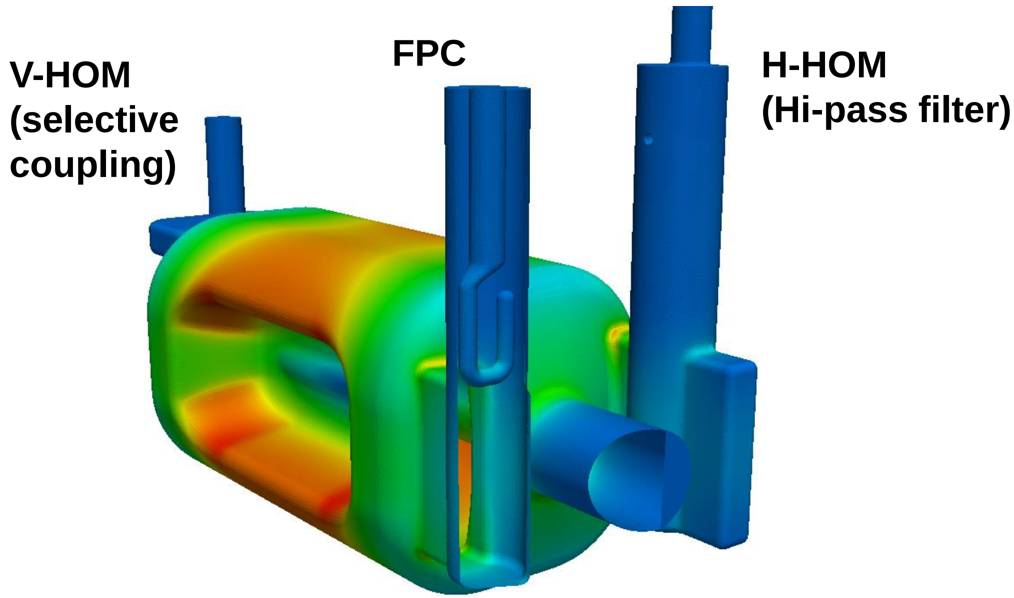
- No lower-order mode
- Frequency of first HOM is about 1.5 that of fundamental deflecting mode





Nearest cavity mode
~230 MHz away

FPC and HOM Coupler Designs

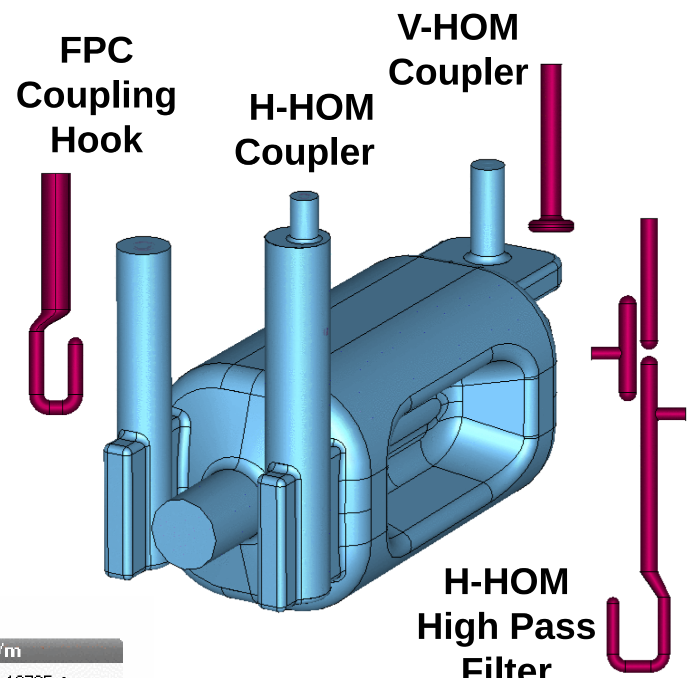


- Coupler at locations of low field region on cavity body
  - Minimizes RF heating on the coupler components
- Location preserves field symmetry
  - Electrical center moved by 50 microns
- Selective coupling (V-coupler) to reduce the number of filters
- FPC/HOM ports oriented to keep clearance for the second beam pipe

FPC and HOM Couplers

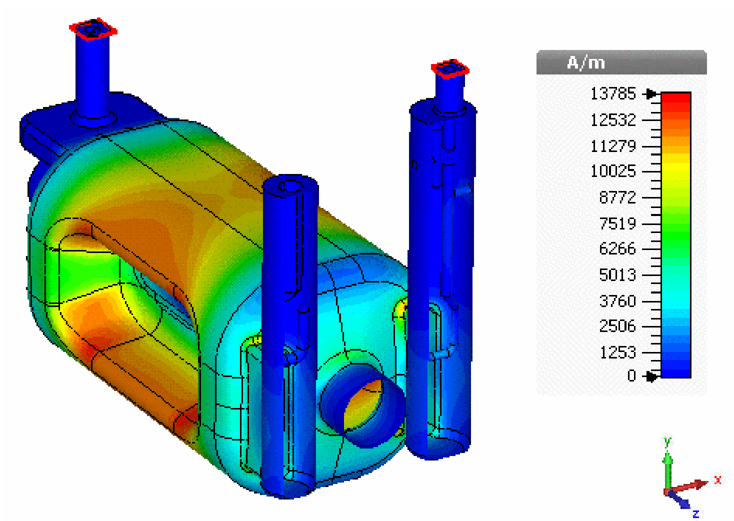
FPC

- Outer diameter – 62 mm
- Inner diameter – 27 mm
- Interface to LHC main coupler design
- $Q_L = 5.0 \times 10^5$
- Hook shaped coupler reduced RF heating → 69 W



V_HOM

- Doesn't couple to fundamental mode
  - No filter necessary
- Damps vertical dipole modes and some accelerating modes

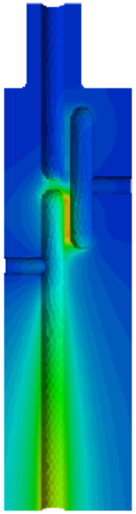


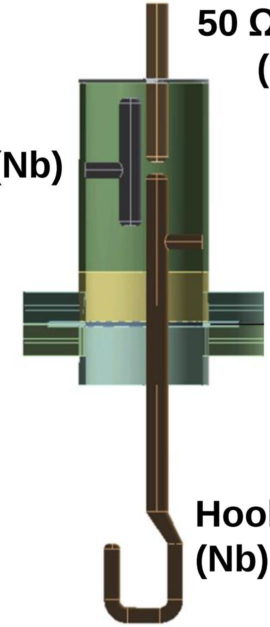
H_HOM

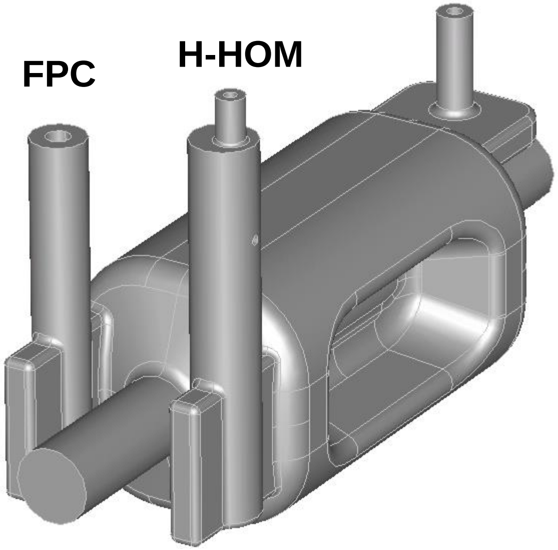
- Horizontal HOM high pass filter to cut off fundamental mode
- Couples to horizontal dipole modes and accelerating modes
- Both options damp adequately to meet impedance requirements

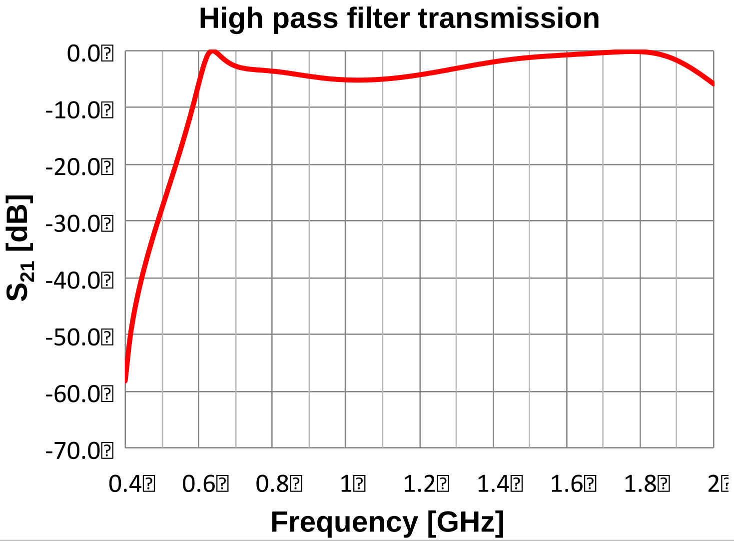
HHOM – High Pass Filter

- High pass filter
  - Simple filter design
  - Damps horizontal deflecting and accelerating modes
  - Demountable coupler
  - Low fields in the filter





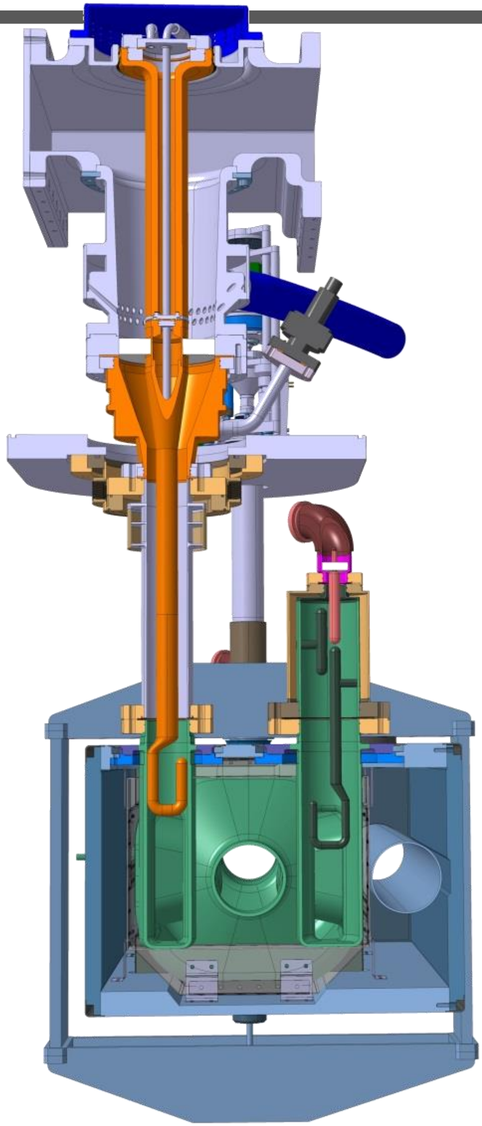




- Dimensions
  - Center rod diameter: 14 mm
  - Larger cylinder diameter: 74 mm
  - 50 ohm port: 14mm/32.2mm

Engineering Activities

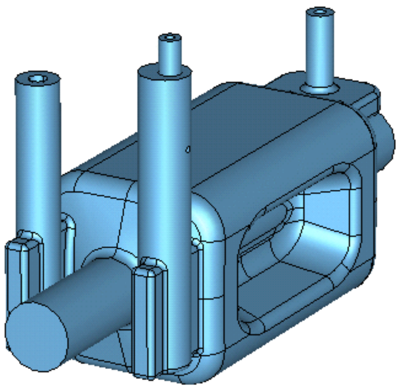
- SPS Cavities under production by DOE LARP
- HOM prototyping to be launched (JLAB or CERN); production for SPS will be done by CERN
- Helium vessel designed by CERN and will be produced by LARP
- Tuning system will be produced by CERN
- Magnetic shielding to be finalized by STFC

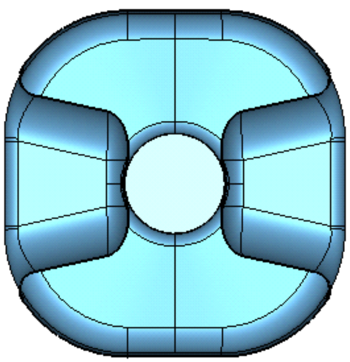


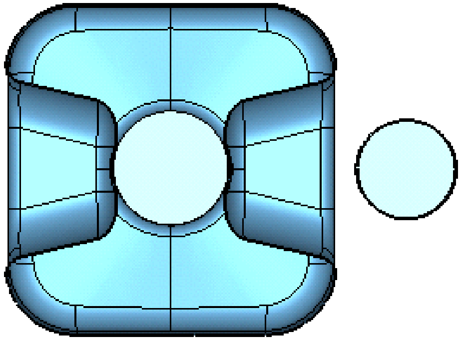
Impact of Beam Aperture (84 → 100 mm)

Aperture	**84**	**100**	**mm**
Frequency	400		MHz
Nearest HOM	633.5	630.0	MHz
E_p^*	3.6	4.2	MV/m
B_p^*	6.2	6.9	mT
B_p^*/E_p^*	1.71	1.66	mT/ (MV/m)
$[R/Q]_T$	429.7	277.7	Ω
Geometrical Factor (G)	106.7	112.2	Ω
$R_T R_S$	4.6×10^5	3.1×10^4	Ω^2
At $E_T^* = 1$ MV/m			

- Preliminary design looks promising
  - Still room for further optimization
- Remains to be done
  - HOM damping
  - Multipole components
  - Multipacting analysis

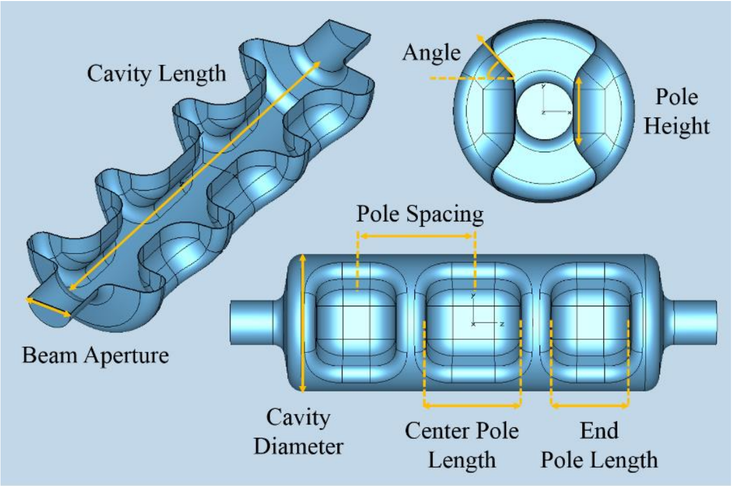


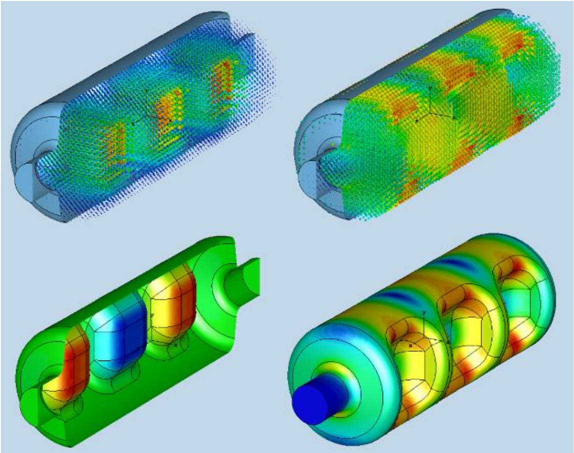


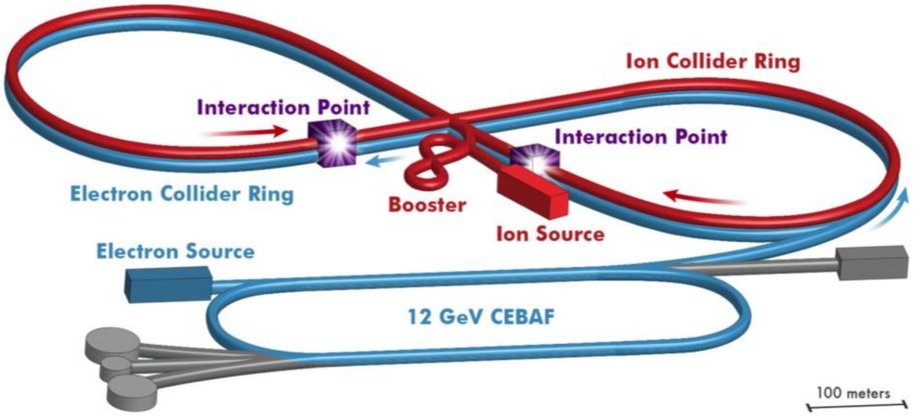


952.6 MHz Multi-Cell Cavity for JLEIC

- A 3-cell design for Jefferson Lab Electron-Ion Collider

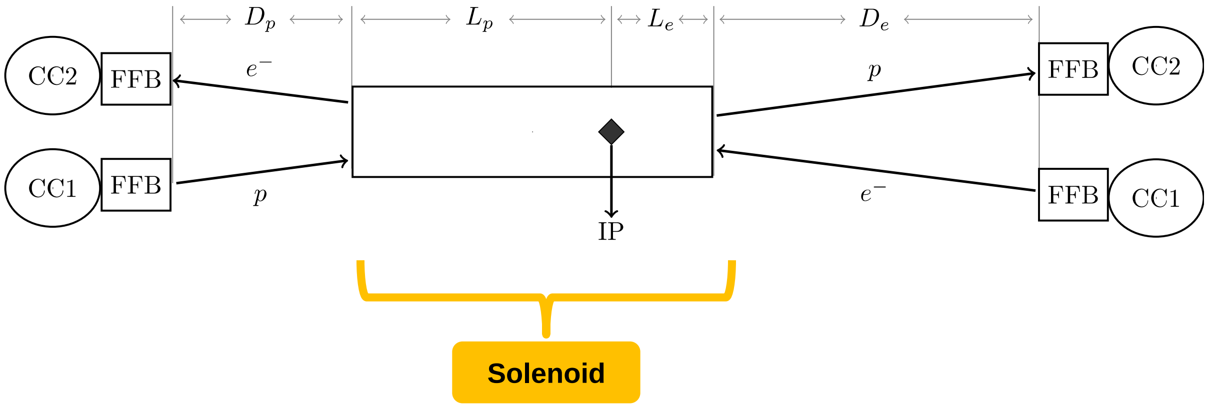






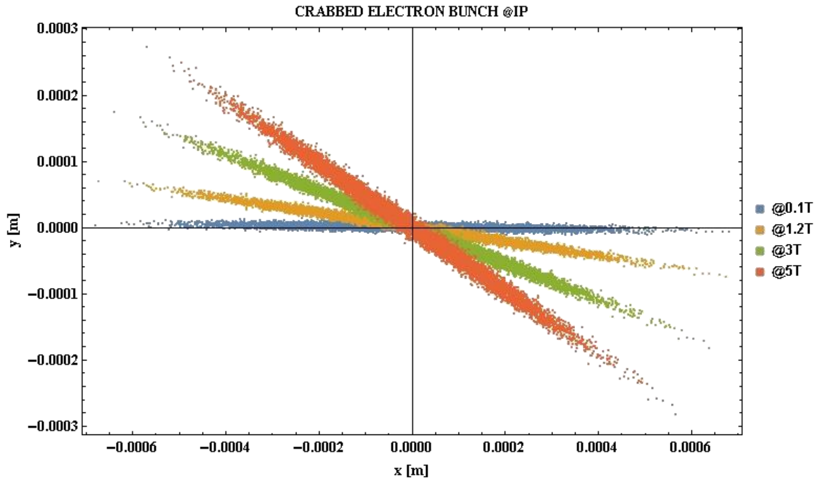
Frequency	**952.6**			**MHz**
Aperture	50	60	70	mm
LOM	790, 879	773, 870	757, 862	MHz
1st HOM	1409	1383	1335	MHz
V_t^*	0.157			MV
E_p^*	4.7	5.1	5.6	MV/m
B_p^*	8.7	10.0	11.4	mT
$[R/Q]_t$	494	323	219	Ω
G	161	170	179	Ω
R_tR_s	8.0×10^4	5.5×10^4	3.9×10^4	Ω^2
$^*E_t$ = 1 MV/m				

Detector Solenoid in the Interaction Region



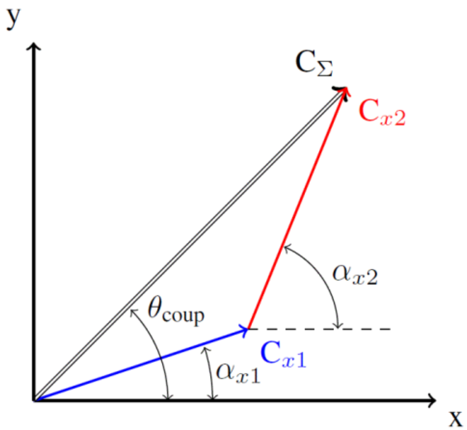
- **If not assessed, this tilt could considerably reduce further the luminosity**

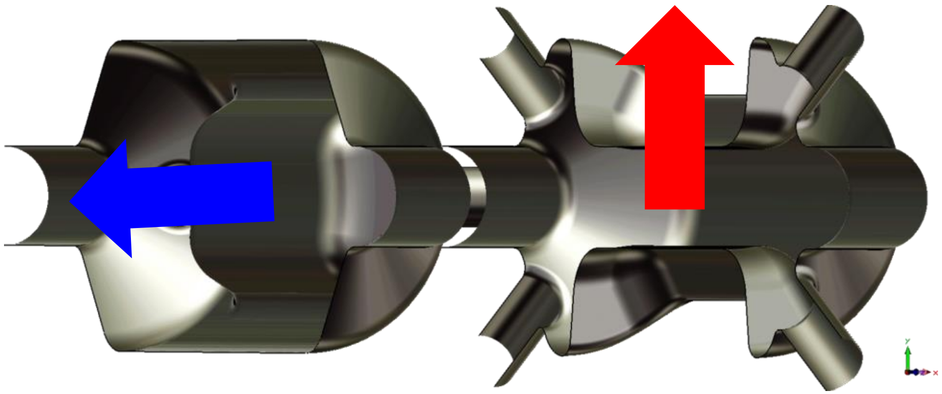
- **Specially important when ramping the solenoid strength**



Twining and Variable Crabbing Kick

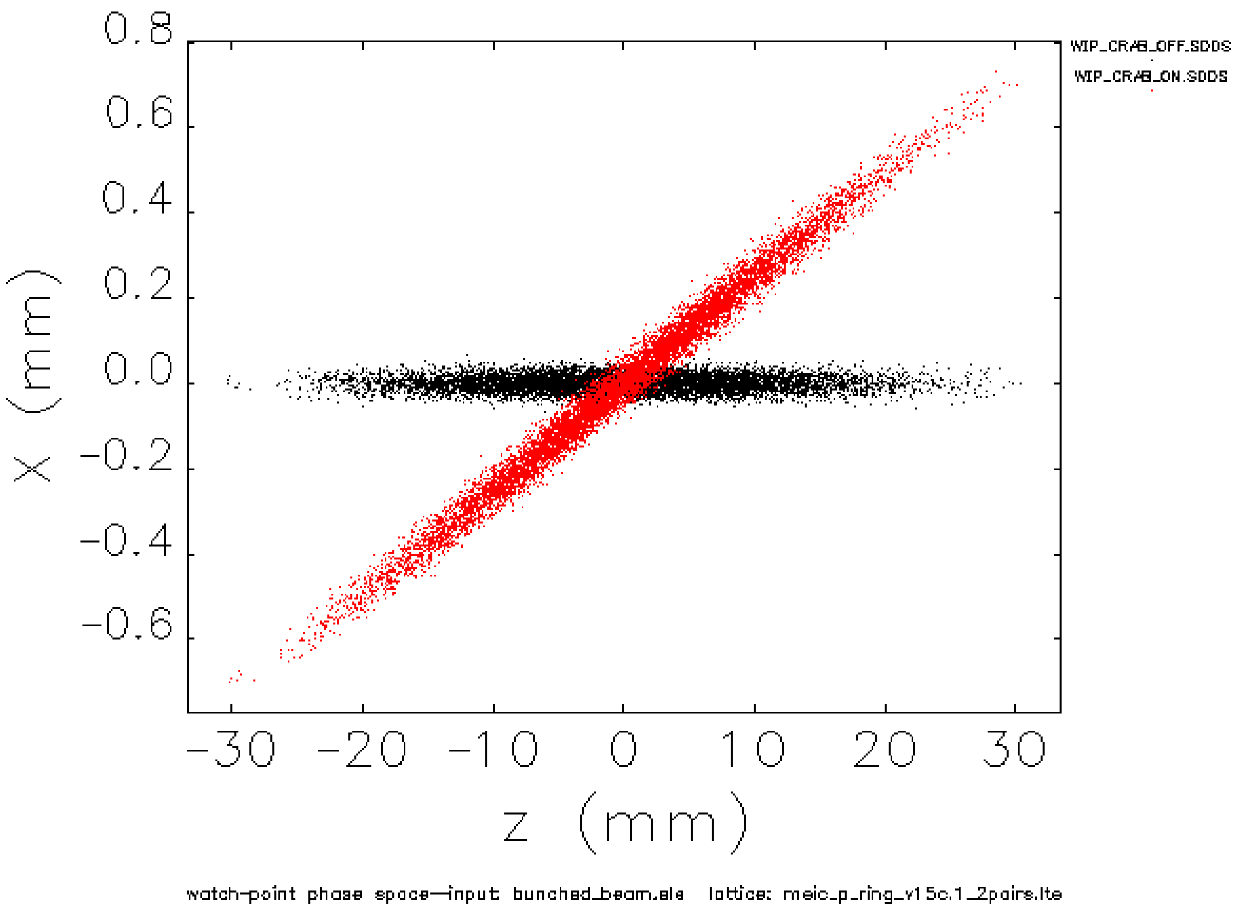
- **A variable crabbing direction is possible with a family of crab cavities with different orientations**
- **The coupling range will determine the angle range to cover by the twins**
- **If the range is small, the twin component of the kick is only a small correction and could be done with 1 or few cavities.**





Bunch at IP with and w/o crabbing

Bunched Beam parameters	
N particles	10,000
ε_{nx}	0.35 µm
dp/p	$3e^{-4}$
σ_s	1 cm
Gaussian distribution 3 - sigma	

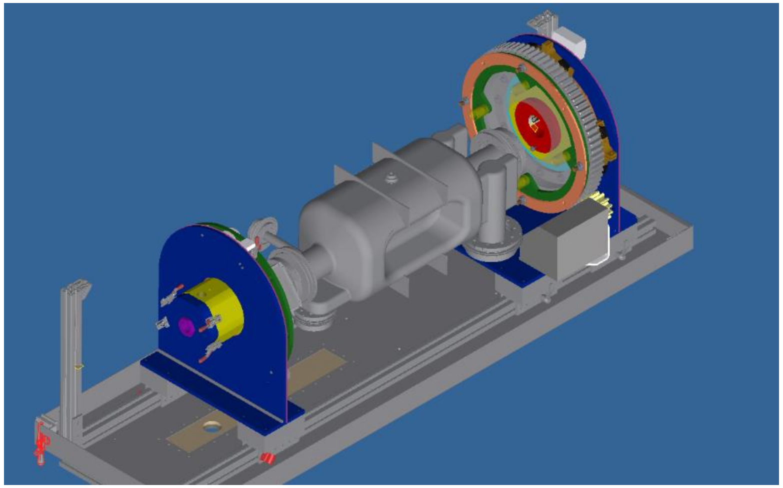


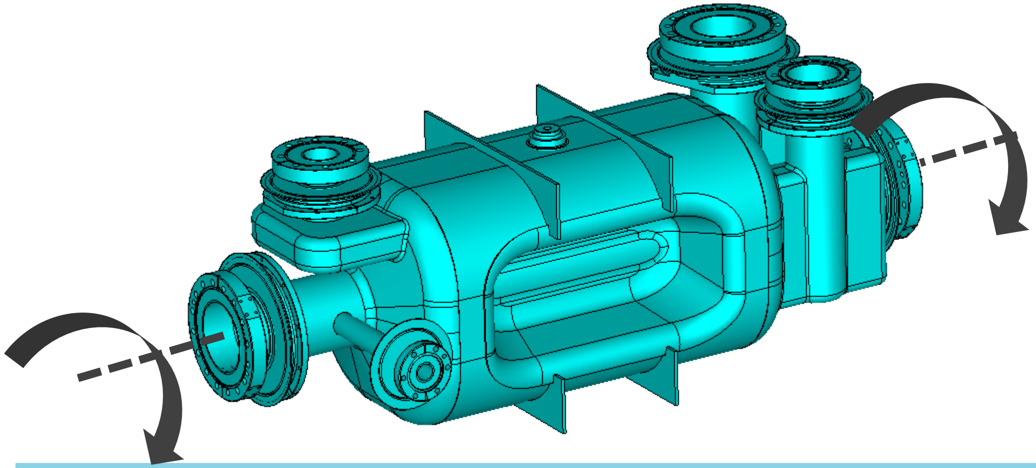
Crab angle ≈ 25 mrad

Recommendations for LHC-RFD – Cavity Processing

- Currently bulk BCP, light BCP and HPR are done in vertical orientation
- Recommendation → Perform chemical processing horizontal orientation with rotation
  - Allows uniform removal
  - Better acid circulation and drainage
- Use of a high pressure rinse set up facilitating multiple port rinsing (Rinsing through FPC and HHOM ports)
  - Allows reducing field emission

Horizontal BCP/EP tool – (ANL)





R&D Plan for Crabbing System for JLEIC

- This R&D plan should take the crabbing system from TRL 2-3 to TRL 4-5 (low to medium)

- Risk: Beam physics requirements could lead to inefficient cavity geometry, or challenging engineering

- Alternative technical approach:
  - Investigate other cavity geometries
  - Investigate process improvements
    - Nitrogen doping
    - Nb_3Sn coating